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FINAL REPORT

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by:
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17 Abstract

A study was undertaken to demonstrate that soil suction can be reliably measured in a track subgrade and to illustrate how suction measurements relate to understanding of subgrade performance and slope stability. Three of several measurement systems considered were used for laboratory and field determination of soil suction, namely:

1) Filter paper method
2) Thermocouple psychrometer method
3) Agwatronics II moisture stress sensor

Five separate field test sites were established on CNR and CPR trackage in western Canada, four in the vicinity of Regina, Saskatchewan; and a fifth near Fort Saskatchewan, Alberta. Site investigations were conducted for each site and field monitoring commenced in the fall of 1984 and continued until the spring of 1985. The laboratory portion of the program included the routine classification and water content determinations of all samples and shear strength and plasticity index determination of representative samples.

Substantial progress in field measurement of matric potential was achieved, confirming that direct measurement of soil suction is possible but additional effort is necessary to create confidence in measuring system.

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17. Résumé

Ce rapport rend compte de la recherche sur la succion capillaire (force de succion du sol) dans le but de montrer que cette force peut être fiablement mesurée dans une plate-forme ferroviaire et que les résultats de ces mesures permettent de mieux comprendre l'état de la plate-forme et de prédire sa stabilité. Trois méthodes de mesure, parmi plusieurs, ont été utilisées pour les déterminations en laboratoire et in situ. Ce sont:

1) le papier filtre
2) le thermocouple-psychromètre
3) le capteur Agwatronics II

Cinq sites éloignés les uns des autres ont été choisis sur es voies appartenant au CN et au CP, quatre dans la région de Regina (Sask.) et un près de Fort Saskatchewan, dans l'Alberta. Des études de reconnaissance des sols ayant été faites, le suivi in situ a commencé à l'automne de 1984 et s'est poursuivi jusqu'au printemps suivant. En laboratoire, tous les échantillons ont été classifiés et leur teneur en eau déterminée, tandis qu'à l'égard des plus représentatifs d'entre eux la résistance au cisaillement et l'indice de plasticité ont été déterminés.

La recherche a débouché sur un perfectionnement notable dans la mesure in situ de la force de succion du sol, montrant la faisabilité des mesures directes de cette force. Il reste cependant à confirmer la confiance vis-à-vis des méthodes de mesure mises en oeuvre.

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1.0 INTRODUCTION

This study was commissioned in recognition of the fact that negative pore water pressures (i.e., soil suction) control the engineering behavior of unsaturated soils, including shear strength, bearing capacity and slope stability. There is presently a desire to incorporate existing knowledge of soil suction into the design and maintenance of railway facilities. To this end a study was conducted to assist in the understanding of the role that soil suction plays in track subgrade performance and in the stability of slopes. This study was supported equally by Canadian Pacific and Canadian National Railways and by the Government of Canada, Ministry of Transport.

1.1 THEORY

Classical soil mechanics considers soils to consist of three distinct phases. They are solid (i.e., mineral particles), liquid (i.e., usually water) and gas (i.e., air) phases. Soils which have their pore spaces completely filled with water are called saturated soils. The state of stress of the water within these pores, greatly influences the shear strength, volume change, hydraulic conductivity and consolidation behavior of the soil. Soils from below the water table are generally saturated. Typically soils in railway subgrades do not fall into this category. These soils are located above the water table and as such are unsaturated.

Unsaturated soils consist of solid, liquid and gaseous phases but can be considered to have a fourth distinct phase. This phase is comprised of the boundary layer between the liquid and gaseous phases. This boundary layer is only a few water molecules thick and has different properties from both the liquid and the gas phases. This layer is commonly referred to as the contractile skin. "Contractile" because of the tendency of the liquid in this phase to contract, and "skin" due to the thickness of the layer. The contractile skin can be thought of as an elastic membrane which surrounds the water and pulls the soil particles together.

As the soil moves from a saturated towards an unsaturated state, the fluid within the voids of the soil changes from water, to that of water with occluded air bubbles. At the point where air enters the system, the soil is no longer saturated. For degrees of saturation greater than 85 to 90 percent, the characteristics of the contractile skin has little effect on the system since it does not interact with the soil structure (Fredlund, 1979) and the soil behaves similar to a saturated soil. Below 85 to 90 percent, however, the air phase becomes continuous and the contractile skin begins to interact with the soil structure. It is the properties of the contractile skin, combined with the physical interaction with the soil structure which largely influences the behavior of unsaturated soils.

The effect of the contractile skin on the soil structure is the major contributor to what is commonly referred to as the suction within a soil. Suction in general terms can be visualized as the demand that a soil places on water or how strongly a soil will hold water (i.e. a soil exhibiting a larger suction will hold its pore water more tightly). Suction is made up of two components, matric suction and osmotic suction. Matric suction is of more interest since it displays the most significant effects on the behavior of soil and because of its close relationship to climate.

The generally accepted definition of the components of suction are as stated by the International Society of Soil Science and as outlined by the review panel of "Moisture Equilibria and Moisture Change in Soil" (Aitchison, 1965). The definitions follow:

Matric suction is the negative gauge pressure, relative to the external gas pressure on the soil water, to which a solution identical in composition with the soil water must be subjected to in order to be in equilibrium, through a porous permeable wall, with the soil water.

Osmotic suction is the negative gauge pressure to which a pool of pure water must be subjected to in order to be in equilibrium through a semipermeable (i.e. permeable to water molecules only) membrane with a pool containing a solution identical in composition with the soil water.

Total suction in the negative gauge pressure relative to the external gas pressure on the soil water to which a pool of pure water must be subjected to in order to be in equilibrium though a semipermeable membrane with the soil water. Total suction is thus equal to the sum of matric and osmotic suction.

The general shear strength equation used in saturated soil mechanics is based on the classical Mohr-Coulomb theory. It was shown by Fredlund et al (1978) that this classical representation could be extended for unsaturated soils to include the effects of matric suction. The proposed extended shear strength equation is as follows:

$$\tau = c' + (\sigma - Ua) \tan\phi' = (Ua - Uw) \tan \phi^b$$

where:

τ = shear strength
c' = effective cohesion intercept
$(\sigma - Ua)$ = normal stress
$(Ua - Uw)$ = matric suction
ϕ' = effective soil friction angle
ϕ^b = slope of the plot of $(Ua - Uw)$ versus when $(\phi - Ua)$ = constant
Ua = pore air pressure
Uw = pore water pressure

A graphical representation of this relationship is included as Figure 2. The influence of matric suction on the soil shear strength can be visualized in this plot. If a soil is saturated, then the matric suction component of suction is zero (i.e. (Ua-Uw)=0). Then the three dimensional representation reverts to the more familiar two-dimensional plot of shear stress versus normal stress for saturated soils. If however, the soil is unsaturated, the matric suction is manifested on the classical saturated Mohr-Coulomb diagram as an increase in the cohesion intercept (Figure 3).

Figure 3 graphically illustrates the effect of soil matric suction on shear strength. The effect of matric suction on the soil shear strength can be visualized as an increase in the cohesion component of the classical shear strength equation. The greater the matric suction, the greater the shear strength of the soil.

2.0 PROGRAM OBJECTIVES

The main objective of this study is to demonstrate that soil suction can be measured in the field and to indicate how suction measurements can be used in the solution of railway engineering problems. More specifically the primary objectives are:

1) To demonstrate that soil suction can be measured in the field in soils typically found in Canada.

2. To demonstrate the manner in which soil suction in the subgrade varies throughout the season as a function of the microclimatic conditions.

3. To test reliability of available suction measuring devices, with primary consideration given to gauges which measure thermal conductivity of a standard porous stone. (Agwatronics moisture stress sensors.)

4. To illustrate how suction measurements relate to understanding subgrade performance and slope stability. These engineering aspects would become the main thrust of future research work under this program.

There was a need to look at several of the systems presently used and being investigated by researchers in the fields of soil science, agriculture and engineering. These systems were evaluated using a practical approach to see how they could be utilized in a field or engineering laboratory situation. Although several of the systems have been in use in research laboratory situations with various degrees of success, there was a need to test their applicability in a field situation. Further, part of the objective was to determine the relationships between laboratory methods and field measurements for determining soil suction using existing laboratory methods as a reference for the proposed field methods. It was recognized that development of field measurement equipment would be required for the Agwatronics sensors.

3.0 AVAILABLE MEASURING SYSTEMS

Several measurement systems were considered for laboratory and field determination of soil suction. The systems used included:

1) The Filter Paper Method based on the published works of:
   a) McQueen and Miller (1968)
   b) Hamblin (1980)
   c) Miller and Bransen (1982)

2) The Thermocouple Psychrometer Method
   a) Brown and van Haveren (1972)
   b) Daniel et al (1979)

3) The Agwatronics II In Situ Method
   a) C.J. Phene et al (1971)

3.1 THE FILTER PAPER METHOD

The Filter Paper Method involves the placement of an air dry filter paper in direct contact with a soil sample (Method 1a and 1b) or suspended above the soil sample in a sealed container (Method 1c). The filter papers are pretreated with a fungicide to inhibit bacterial decomposition.

Method 1a and 1b

The action of air drying the filter paper imparts a relatively high suction to the filter paper when compared to the suction within the soil. When the filter paper is placed adjacent to and in direct contact with a sample of soil, the soil water is subjected to a stress or suction. This suction causes the pore fluid to pass from the soil to the filter paper by direct contact or fluid flow. Although some of the water will enter the filter paper by vapour flow, this method does imply some direct contact or fluid flow. The high suction within the air dry filter paper causes the water within the soil to flow from the soil (i.e. zone of higher vapour pressure, higher suction), or down gradient from a high pore water potential to a low pore water potential. This flow will continue until the differential pressure or differential stress on the pore fluid is satisfied. When this occurs, the filter paper and the soil are applying the same stress on the pore fluid. That is, the suction within the filter paper is the same as the suction within the soil and the system is said to be in equilibrium. At equilibrium the fluid within the filter paper is assumed to be of similar chemical composition (i.e. salt concentration) as the soil pore water. Therefore no osmotic suction is established and the measured potential is matric suction. Given that the filter paper is small in comparison to the soil sample and the amount of flow is small. The suction established within the filter paper is essentially the same as the initial suction within the soil sample.

Method 1c

Similarily when the filter paper is placed within a sealed container suspended above the soil sample (i.e. no contact) the filter paper gains water from the soil through the vapour phase. With this method the concentration of salts within the soil pore water results in an osmotic potential difference being established between the soil pore water and the filter paper across the vapour barrier.

This potential is established since the water will flow from the region of high vapour pressure (i.e. the filter paper pore water) to a zone of low vapour pressure (i.e. the soil pore water). The presence of salts within the soil water exerts a suction within the water held by the filter paper. This suction is a result of both the matric suction and the osmotic components or total suction.

The different methods employed indicate that the component of suction measured is a function of the method used in measurement. With the proper technique it is possible to determine the matric suction within a soil by determining the water content of the filter paper, after allowing the soil-water-filter paper system to reach equilibrium.

For this study filter papers were allowed to equilibrate for at least one week prior to determining their water contents. The water contents were then used to determine the suction within the soil sample. Several questions arose out of the filter paper test methods. These questions are addressed later in this report.

A considerable amount of work has been done by others (i.e. Gardner, 1936, McQueen and Miller, 1968, Fawcett and Collis-George, 1967, Hamblin, 1981, Gallen, 1985) to establish a fixed relationship between filter paper water content and suction. Typical calibration curves relating these two parameters, for the various filter papers used in this study, are appended.

3.2 THERMOCOUPLE PSYCHROMETER METHOD

The Thermocouple Psychrometer measures total suction by making use of the Peltier effect to measure the relative humidity above a soil sample within a sealed chamber. A thermocouple psychrometer is capable of measuring suction in the range of -1 to -80 bars or -100 to -8000 kPa.

A psychrometer consists of a measuring junction of copper and constantan. The reference junction is also utilized in measuring the sensor temperature. The construction of a typical three wire thermocouple psychrometer is as illustrated in Figure 4.

A sample of soil is sealed in a chamber with a psychrometer. Initially the dry air above the sample exerts a stress on the soil pore water. This stress causes water to be extracted from the soil into the air above the soil by vapour flow. This flow or evaporation ceases when the differential stress exerted on the pore water by the soil and the air above it is satisfied. If the soil has a high suction then the air will draw a lesser amount of pore water from the soil resulting in the air having lower water content (low relative humidity). Conversely, if the soil has a lower suction the dry air competing for the pore water will withdraw a greater amount of pore water, resulting in a higher water content (relative humidity). When a current is passed through the chromel constantan measuring junction, the junction cools (Peltier Effect). This cooling causes a droplet of water to condense on the measuring junction. When the cooling current is turned off, the water droplet begins to evaporate. This evaporation causes further cooling at the measuring junction. The rate of cooling is a function of the relative humidity within the chamber or the stress which is placed on the water droplet to return to to the vapour phase. The higher the relative humidity the longer the time required for the droplet to evaporate. The thermocouple psychrometer meter indicates the difference in temperature, after given time, between the measuring junction and the copper chromel reference junction.

The output from the psychrometer is a voltage difference in microvolts. This output voltage is then related to soil suction by utilizing a calibration curve for each psychrometer. This relationship is established by determining the psychrometer output in microvoltts after placing the psychrometer above a saturated filter papaer within the sealed chamber. The filter paper is saturated with an aqueous solution of NaCl (sodium chloride). The filter paper in this case was only used as a media for the aqueous solution and is otherwise not related to the suction established. This procedure is performed several times for each psychrometer using different strengths of NaCl solution. The different solution strengths provided a series of known suctions which then could be related to the psychrometer output. This data is then used to determine a calibration equation for each specific psychrometer. Copies of the calibration data are attached.

3.3 THE AGWATRONICS IN SITU METHOD

The primary in situ measurement system considered was based on the Agwatronics II sensor manufactured by Agwatronics Inc. of Merced, California. The sensor consists of a thermistor and a 20 ohm heater embedded within a porous ceramic block. The moisture stress sensor measures matric suction by utilizing the heat dissipation characteristics of the porous material and the material within the pores. The rate of heat dissipation in a porous body is related to the thermal conductivity (KO and the density (ρ) of the material and on its specific heat (C). For homogeneous isotropic materials whose thermal

conductivity is not related to temperature, a useful relationship is known as diffusivity (D) where:

$$D = K/\rho C$$

For any substance, thermal conductivity is a function of the materials of which it is made. A porous material is a composite made up of a matrix material (i.e. ceramic), and the fluid within the pores. The thermal conductivity of the matrix is much lower than that of water and as such the amount of water within the pores greatly influences the thermal conductivity of the sensor block. As the water content of the block increases the thermal conductivity is reduced.

When the sensor is initially positioned in contact with soil there is a difference in suction between the water in the sensor and the soil pore water. The direction of flow depends on the potential gradient. Water will always flow from a zone of high potential to a zone of low potential (low suction to high suction) in order for equilibrium to be reached. This flow is either by fluid flow or vapour diffusion.

The temperature of the sensing block is initially determined by measuring the resistance of the thermally sensitive resistor. A controlled amount of heat (constant current source for a specific time) is added to the center of the block, then the temperature is again determined. Since the thermal characteristics of the porous block material itself does not change (i.e. the ceramic), the rate of which the heat dissipates is directly related to the water content of the porous block. A relationship between water content of the sensor block or rate of heat dissipation of the block and the soil matric suction is then established.

Sensor calibration was performed by Agwatronics Inc. The calibration procedure involved mounting the sensors in a pressure plate apparatus and then subjecting the sensors to a known negative pressure. The change in output voltage of the thermally sensitive resistor after being subjected to a constant current, was then related to the established suction. A linear relationship was established between matric suction and the change in temperature of the block as expressed by a change in voltage in millivolts.

Measurements are made in situ with the aid of a hand held meter. The meter supplies a constant current source to the heater within the sensors and measures the temperature of the block before and after the heating cycle. The change in temperature (voltage) is read directly from a liquid crystal display after the read cycle is complete. Several difficulties were encountered with the readout device during this study. These problems will be addressed later in this report.

4.0 PROGRAM EXECUTION

4.1 SITE SELECTION

Four sites located in western Canada, were selected for the field program. Subsequently, a fifth site was added. The sites were selected on the basis of material type and proximity to major urban centers for ease of access. Site Nos. 1 to 3 are situated in highly plastic clay, Site No. 4 in till and Site No. 5 is in silty clay. Site No. 1 is located in an older subgrade which has not failed but is a continuing maintenance problem. Site No. 3 is located within a new subgrade, constructed within the last few years. Site No. 4 is located in a high traffic section showing no distress. Site No. 5 is located in a large fill section that is currently performing well.

Site Nos. 1 through 4 are all located within a 60 kilometre radius of Regina. Site No. 5 is located near Fort Saskatchewan, Alberta. The location of each site is as indicated on the location plan included as Figure 5.

The sites are located as follows:

SITE NO.	LOCATION	SYSTEM	MILEAGE & SUBDIVISION
1	Belle Plaine, Sask.	CNR	Mile 24.3 CB01
2	Bechard, Sask.	CNR	Mile 78.3 Lewvan Sub.
3	Regina, Sask.	CNR	New Lewvan Bypass
4	McLean, Sask.	CPR	Mile 67.2 Broadview Sub.
5	Fort Saskatchewan, Alta.	CNR	Mile 2.14 Beamer Sub.

4.2 FIELD MEASUREMENT

A site investigation was carried out at each of the above locations. The investigation included the gathering of representative disturbed and undisturbed samples for laboratory visual classification and index testing, followed by laboratory suction measurements. All sites were instrumented by installing a prefabricated 915 mm diameter culvert vertically 6 m below the top of the tie elevation. The culvert was located directly off the end of the ties. AGWA II sensors were installed at predetermined depths below the subgrade through the vertical wall of the culvert. A typical detail of this installation is illustrated in Figure 6. The locations of the sensors for each site is as indicated on the respective bore hole logs included in this report. A standpipe piezometer was installed at each site to monitor the ground water levels.

4.3 FIELD MEASUREMENT

The field monitoring of the Agwatronics II sensors was initially performed with a hand held readout device. In the early stages of the program the sensors located within the Regina area were read every one to three days. The Edmonton site was read on a less frequent basis with the same readout device. Towards January and February of 1985, the frequency of readings was somewhat reduced. During the month of March an automated data acquisition system (data logger) was put into service. This method of data collection allows for automated collection of data at an increased frequency. Initially the data logger was used in a manual mode to read all of the sites in the Regina area. This was done to establish a correlation between the manual readout device and the data acquisition system. The data acquisition system was then installed at Site No. 1 where the performance of the system could be easily monitored readily. The data logger was initially set to read the sensors at hourly intervals.

4.4 LAB TESTING PROGRAM

The laboratory portion of the program included the routine classification and water content determinations for all samples. Plasticity index testing and the measurement of soil suction by the laboratory methods as described were performed on several representative undisturbed samples. The undrained shear strengths were also determined on several representative samples. The majority for the testing was performed on a representative soil column obtained by continuously sampling from one borehole at each of the sites.

5.0 PRESENTATION OF DATA AND DISCUSSION OF RESULTS

5.1 SITE BY SITE DISCUSSION

The following discussion makes use of a study entitled "Comparison of Porewater Potential Components" (Krahn, 1970). Reference is made in the folowing text to typical or expected values for matric and total suctions for a typical "Regina Clay" and for "Indian Head Till". Although these materials were not obtained from the sites under study here, the materials are similar to those at several sites, allowing the values to be used for comparison purposes.

5.1.1 SITE NO. 1

Site No. 1 is located on CN trackage near Belle Plaine, Saskatchewan. the track condition at this location is poor with much effort devoted annually to lift and align the track. This line is used as a spur line into a large Potash mine and as such is subjected to heavy loading. Much of the difficulties associated with this section of track is because the line has bearing capacity failures for most of its length on both side slopes (1979 - CAL Report #R112). The annual difficulties experienced with this section of track is one of the primary reasons this track was selected.

The stratigraphy consists of 460 mm of gravel ballast and subballast overlying 5.6 m of stiff, highly plastic clay. The clay is underlain by a stiff to hard glacial till at the 6.1 m depth (Figure 7). A stand- pipe piezometer was installed with the tip 9 m below grade. The piezometer remained dry for the duration of the project but a small amount of seepage entered the culvert during the spring breakup period (Figure 8).

The Agwatronics moisture stress sensors were installed on November 7, 1984. The sensors are installed saturated and in the order of 30 to 40 days was required for equilibrium to be reached in the sensor - soil - water system (Figure 9). By this time all but the occasional sensor had responded. Most of the sensors appeared to have reached equilibrium or showed movement towards equilibrium by mid February 1985. Shortly thereafter, the sensors began to freeze in response to the advancing frost line. During the equilibration time the suction measurements climbed as the excess water within the sensor was drawn out by the suction within the soil. After some time the sensors appeared to stailized with only a few departures from this trend. It is not known at this time whether these periodic fluctuations are indeed variations in actual suction values or whether they are related to the atmospheric temperature influences on the manual readout device or due to the temperature variations themselves. For the purposes of comparison the data obtained in the field on December 12, 1984 will be used. This corresponds to 35 days after installation.

Based on the status of the data collected to date, the Agwatronics sensors indicated a matric suction ranging form 75 to 250 kPa for the surificial clays. The suction profile was "S" shaped. Higher suctions were noted near the top of the subgrade just underlying the ballast, then a slight decrease, then increasing again, and finally decreasing with depth (Figure 10).

If gravity was the only force acting on the system, the shape would approach a straight line progressing upward and negative from the water table towards the ground surface. The environmental effects on the system caused by dessication and subsequent re-wetting cycles causes this shape to be deformed to the more classical "S" shape. This shape is clearly seen on most of the suction profiles measured with Agwatronics sensors.

Close agreement was noted when comparisons were made using typical suction values for a "Regina Clay". The matric suction is expected to be in the range of 100 to 250 kPa. Tests were conducted using the McQueen and Miller filter paper method in the laboratory on undisturbed samples obtained in the field investigations. The matric suctions determined were in the range of 20 to 3000 kPa (Figure 11). A large amount of scatter is evident in the filter paper test results. The peak values are attributed to the measurment of total suction.

Tests were also conducted using Hamblin's Filter paper technique (Figure 12). Even less agreement was found. The values obtained were in a range of 50 to 250 kPa with an average of 60 kPa. It was found that generally the Hamblin technique gave consistently much lower values for matric suction than the other methods.

The total suction component for the clays materials at the water contents measured, is thought to range from 200 to 450 kPa. Total suction values of 50 to 1800 kPa (typically 400 kPa) were determined using the technique based on the McQueen and Miller method (Figure 13). Tests performed using the Psychrometer method indicated a total suction varying from 260 to 600 kPa. The suctions determined by the psychrometer method indicated a good agreement with values expected (Figure 14). The filter paper method, on average, was similar however, the degree of scatter in the test results was significantly greater.

Within the till at depths below 6.1 m the typical range for matric suction is thought to be from 100 to 175 kPa at these water contents (after Krahn, 1970). The McQueen and Miller filter paper method indicated suctions in the range of 325 to 700 kPa which indicates poor agreement with values for total suction, typically 300 to 475 kPa. This illustrates one of the recurring problems associated with the use of the filter paper method. That is, at lower water contents there is insufficient pore fluid to pass in to the filter paper directly. The filter paper, although in contact with the soil, gains water by vapour

diffusion or through the vapour phase. In gaining water in this manner the filter paper reflects total suction. In this case the filter paper method measured total suction while attempting to measure matric suction. Hamblin's method showed good correlation to the expected values and indicated a range of suction from 75 to 225 kPa. The total suction as determined for the till with the psychrometer method also showed a close agreement with the filter paper method (range 170 to 775 kPa) by indicating suction varying from 460 to 660 kPa.

The overall trend of matric suction with depth at this site as determined by the filter paper techniques is similar to the classical "S" shape as described above. The total suction profile is more linear with respect to depth on a semi-log plot (Figure 14).

5.1.2 SITE NO. 2

This site is located on CN trackage south of Bechard, Saskatchewan. The track condition at this site is poor and requires periodic maintenance. This line is a branch line with the principle commodity transported is grain.

The stratigraphy consists of 760 mm of gravel ballast and sand subballast overlying 1200 mm of stiff, highly plastic clay. This clay was strongly organic in nature. Underlying this clay is stiff to hard highly plastic clay which becomes less plastic just above the glacial till contact at the 7.9 m depth. The till was stiff to hard (Figure 15). A standpipe piezometer was installed with the tip 9.4 m below top of tie. The piezometer was initially dry but later indicated a water level 5.4 m below grade (Figure 16).

The Agwatronics sensors were installed at this site on November 8, 1984. The data collected on December 13, 1984 will be used for comparison. This corresponds to an elasped time of 35 days. At this time all but the sensor located at 900 mm depth had responded (Figure 17). As at the previous site the Agwatronics sensors were installed only within the surficial clays. The matric suctions as determined by the Agwatronics sensors indicated a range from 130 to 225 kPa with an average of 160 kPa (Figure 18). This agrees closely with the typical range of values as determined by Krahn (1970) for similar clay materials at similar water contents. For a typical "Regina Clay" corresponding to these water contents, matric suction was found to be in the range of 50 to 200 kPa.

Both of the filter paper methods showed some disagreement with the results for the clays at this site. The McQueen and Miller method indicated a range from 140 to 2000 kPa with an average of 1075 kPa (Figure 19). This major departure from expected values can be attributed to a combination of insufficient equilibration time, and in this case, it is believed that the filter paper sensors did not gain

water by direct fluid flow, but rather by vapour flow resulting in the measurement of total suction. This problem was later identified for several matric suction test series.

The Hamblin method for measuring matric suction showed a range between 40 and 600 kPa with an average of 300 kPa (Figure 20). These measurements agree poorly with the expected matric suctions but closely with the total suction for both the expected values and those determined by the psychrometer method. This phenomenon further confirms the difficulties associated with the filter paper method. The filter paper measures total suction regardless of the contact between the filter paper and the soil. The expected range for total suction is between 125 and 350 kPa. The filter paper method for total suction indicated from 150 to 400 kPa with an average of 240 kPa (Figure 21). The psychrometer method indicated a range from 280 to 650 with an average of 490 kPa indicating a close agreement between the expected values and the filter paper method for total suction. The readings obtained from the psychrometer were slightly higher on average but upon comparing these readings with the filter paper results for total suction, it can be seen that the spikes of the total suction plot for the filter paper method lie closely to the total suction curve as outlined by the psychrometer (Figures 21 and 22). This would indicate some agreement but does not explain the lower values of the filter paper method. It is believed that the lower values wre caused by condensation droplets forming on the filter papers within the sealed container during the equilibrium period. This would dramatically increase the filter paper water content thus indicating a substantial decrease in suction.

The matric suction expected within the till at the observed water contents lies within a range of 150 to 350 kPa. The McQueen and Miller method showed good correlation by displaying a range from 20 to 375 kPa with an average value of 180 kPa. The Hamblin method showed its characteristic lower range of 20 to 65 kPa. The total suction as determined by the filter paper method fell within a range of 180 to 250 kPa while the psychrometer measured a range between 310 and 470 kPa. The psychrometer in this case shows excellent agreement with the expected values for total suction. The filter paper method does indicate a much lower value than either the expected values or the psychrometer method.

The overall trend of matric suction with depth at this site as determined by the Agwatronics technique is similar to the classical "S" shape on an arithmetic plot.

5.1.3 SITE NO. 3

This site is located on CN trackage near Regina, Saskatchewan. This line was recently moved to make way for the construction of the new

Lewvan Expressway in the City of Regina. The track condition is excellent. Recent construction and compaction were primary reasons for the selection of this site.

The stratigraphy consists of 460 mm of gravel ballast and subballast. Underlying the ballast is stiff to hard highly plastic clay which becomes less plastic just above the clayey-silt contact at 5.8 m. The underlying silt has a thickness of 800 mm. Till was encountered below the silt and had medium to stiff consistency (Figure 23). A piezometer was installed with the tip 9.1 m below top of tie. After the water levels stabilized in the standpipe piezometer a water level 4.7 m below grade was measured (Figure 24).

The Agwatronics sensors were installed at this site on November 8, 1984. The data collected on December, 1984 indicated that two of the sensors had not yet responded. By February 14, 1985 all sensors were responding well (Figure 25). The Agwatronics sensors were installed only within the surficial clays. The matric suction as determined by the Agwatronics sensors indicated a range from 60 to 275 kPa with an average of 160 kPa (Figure 26). This agrees well with values expected.

The filter paper methods used for matric suction determination did not agree as well. The McQueen and Miller method indicated an average suction value in the clays of 800 kPa with a range of 400 to 5000 kPa (Figure 27). The Hamblin method indicated a range of 175 to 1100 kPa, with an average of 390 kPa (Figure 28). This is even high when compared to the expected values for total suction, but does agree fairly well with the psychrometer method which indicated a range of 575 to 1575 kPa and an average of 920 kPa (Figure 30). Close agreement was also noted with the no contact method filter paper technique with a range of 675 to 1500 kPa and an average of 1360 kPa (Figure 29). This again supports the belief that when attempting to measure matric suction with the filter paper technique, total suction is often measured inadvertently.

A poor correlation was found with the "expected" values for matric suction within the till for both of the filter paper methods. For the typical till referenced (Krahn, 1970), at the water contents measured, the matric sutions are in the order of 175 to 275 kPa. However, the McQueen and Miller method indicated an average of 35 kPa with a range of 15 to 125 kPa (Figure 27), while Hamblin's method indicated 40 kPa with a range of 15 to 55 kPa (Figure 28). This does indicate a good correlation between the two measurement systems for this case. The total suction measured was lower than the typical values expected as well, but did show a slightly better correlation with the "expected" values displaying a range of 225 to 375 kPa with an average of 310 kPa.

As shown on the plot of matric suction versus depth by the Agwatronics sensors (Figure 26), the overall trend with respect to depth once again has the typical "S" shaped curve. However, there are some differences when compared with the first two sites. At this site the initial suction values are lower, then increase slightly with depth, and then drop off rapidly to a lower value towards the water table. The shape of the matric suction curves for the filter paper techniques are similar. The total suction profile has a similar shape, however it is not as evident on a semilog plot (Figure 30). The same data is replotted on an arithmetic scale (Figure 31).

Site No. 3 is of special interest since the subgrade was just recently constructed. The plot of shear strength versus depth as illustrated on borehole log No. 3-1 (Figure 23) is of particular interest. The overall shape shows a high degree of correlation with the suction profile as indicated by the Agwatronics sensors for February 14, 1985. This is expected as an incease in matric suction results in a direct increase in the shear strength in the soil. The plot of shear strength by both the vane shear and pocket penetrometer methods, indicate an undrained shear strength of 200 kPa near the top of the subgrade dropping off rapidly to 100 kPa at the 3 m depth. The shear strength is maintained at this value and only slightly increases when the siltier material is encountered at the 5.8 m depth and then increases slightly again within the till material. The reason for the increase is shear strength near the surface is attributed to both the increased suction and possibly the compactive effort applied during construction.

5.1.4 SITE NO. 4

Site No. 4 is located on the CP main line 3.5 km east of McLean, Saskatchewan. The site, founded almost entirely on till, is subjected to large traffic volumes of various loadings and is performing well.

The stratigraphy at this site is by far the most uniform of all the sites studied. The surficial strata consists of 760 mm of gravel ballast and subballast. Underlying this strata is 740 mm of stiff to very stiff silty clay matrix till. This material is believed to be "fill". Stiff to hard till was encountered below the fill at the 1.5 m depth (Figure 32). A piezometer was installed with the tip 9.1 m below the top of the tie. The piezometer was initially dry but subsequently indicated a water level 6.6 m below grade (Figure 33).

The Agwatronics sensors were installed at this site on November 8, 1984. The data collected on Decebmer 12, 1984 indicated that one of the sensors had not yet responded. By February 15, 1985 all sensors were responding well (Figure 34). The first three Agwatronics sensors were installed within the till fill. The bottom three sensors were installed in undisturbed till. The sensors measured a range of 60 to

160 kPa with an average of 100 kPa (Figure 35). When compared to the expected values for a typical till material as outlined by Krahn (1970) these values are low. The expected range is from 300 to 450 kPa. The McQueen and Miller filter paper technique indicates a matric suction of 225 to 575 kPa with an average of 370 kPa (Figure 36). This agrees closely with expected range. The Hamblin method again shows a lower range of 55 to 80 kPa (Figure 37).

The expected range for total suction is from 675 to 920 kPa. The filter paper method for determining total suction indicates a range of 650 to 1050 kPa with an average of 900 kPa (Figure 38). The psychrometer indicated a range of 260 to 620 kPa for an average of 425 kPa (Figure 39). This indicates poor agreement between the two methods for determining total suction. The psychrometer results do however agree closely with the measurements of matric suction by the McQueen and Miller method (Figure 36).

The overall shape of the suction profiles, on the semilog plots, is more linear than the other sites investigated. All indications are that the actual matric suction of the till at this site is in the ragne of 100 to 300 kPa, with a total suction only slightly greater at 400 to 600 kPa. The one measuring system which did not comply with these values was the filter paper technique for measuring total suction. It is possible that the seven day equilibration time allowed for this method in combination with the size of the air space above the sample within the chamber resulted in insufficient time being allowed for equilibration. This would explain the much higher values obtained.

5.1.5 SITE NO. 5

Site No. 5 is located on CN trackage near Fort Saskatchewan, Alberta. The site was selected because it was a large fill section and because the foundation materials were silty in nature.

The stratigraphy at this site was by far the least uniform. It consists of 1100 mm of gravel ballast and subballast. This stratum ws frozen to 500 mm at the time of the investigation. Underlying this was 4.7 m of stiff to very stiff silty clay fill material. A 300 mm thick layer of organic topsoil and rubble was encountered at tne 5.8 m depth. Stiff, silty clay was encountered below the organic layer at the 6.1 m depth. Fine to medium grained, water bearing sand was encountered at 7.9 m (Figure 40). A piezometer indicated a water level at 6.1 m (Figure 41).

The Agwatronics sensors were installed on October 30, 1984. All of the sensors were installed within the silty clay fill material. The range of suctions observed with this method is from 0 to 200 kPa with an average of 175 kPa (Figures 42, 43). The lower value of the range is attributed to a sensor which had not yet responded (i.e. measuring zero

matric suction in the saturated state). A range of 150 to 225 was expected. The matric suction as determined by the McQueen and Miller method showed a range of 75 to 400 kPa with an average of 175 kPa (Figure 44). All of these three agree closely. Attention again is drawn to the apparent high value of matric suction, as determined by the McQueen and Miller method, at the 2 m depth. This pint agrees closely with the expected value for total suction and the value determined by the psychrometer method (Figure 47). The Hamblin method indicated a small range varying from 40 to 70 kPa (Figure 45).

The total suctions are expected to be in a range of 325 to 450 kPa at these water contents. This agrees quite closely with the filter paper method (Figure 46). The psychrometer showed a good correlation, indicateing a range of 125 to 365 kPa with an average of 280 kPa.

Except for the Hamblin filter paper method at this site all methods agree with expected values.

The suction profile as determined by the Agwatronics sensors indicates the classical "S" shaped curve. The matric suction is 100 kPa near the surface and drops towards zero at the 5 m depth. At the same time the total suction varies from a high of 300 to a low of 200 kPa. Both these measurements can be seen on Figure 44. Note how the measured suction jumps from matric to total with depth indicating that "good contact" between filter paper and soil does not ensure matric suction measurement. The plot of matric suction versus depth for the McQueen and Miller method at this site illustrates the problems encountered with the filter paper method.

5.2 COMPARISON OF MEASUREMENT SYSTEM

5.2.1 FILTER PAPER METHOD

Plots of suction versus depth for all methods are included in this report. The plots indicate varying trends of suction versus depth. Site No. 3 shows the classical shape of high suctions near the surface, dropping off asymtotically towards zero near the water table (Figure 31). On many of the plots of matric suction an occasional spike of high suction can be seen (Figures 11,20,27,28,36,44,45). It is believed that these spikes are not high matric suctions but are actually total suction measurements obtained while attempting to measure matric suction. This would indicate that when using the filter paper method, a given test may measure either matric or total suction. This is shown throughout the testing especially with the McQueen and Miller method. In almost all cases the matric suction measured values wre either close to the expected range or were substantially greater. When greater, there was typically good agreement with other measurements of total suction for the same samples. The Hamblin method for measuring matric suction was approximately the same as the McQueen and

Miller method but consistently indicated lower suction values. When reviewing this method it was found that there was a discrepancy between the original data and the calibration equations difficulties with this method. It is speculated that the composition of the filter paper used in this study may be different than that used in the original work. If there is the case the calibration equations derived from the original published work would not apply.

The filter paper technique used in measuring the total suction was based on the McQueen and Miller filter paper technique. The measurements of total suction using this technique seemed to work reasonably well. However, there were some difficulties relating the results of this method to the results obtained by the psychrometer method in the surficial clays. It should be noted that when there was disagreement, the results of the filter paper technique were usually higher than the psychrometer method. The results of the filter paper method did however agree fairly well with the "expected" values for clays at the corresponding water contents.

5.2.2 THE PSYCHROMETER METHOD

This method showed good correlation between the values measured and the expected values, and an even better correlation between this method and the filter paper method for the measurement of total suction. In several cases, the total suction as determined by the psychrometer method agreed with the "matric suctions" measured by the filter paper method.

5.2.3 AGWATRONICS MOISTURE STRESS METHOD

The results obtained utilizing this system show a definite variation in suction with depth and over time. The variation of suction for a particular sensor with respect to time is primarily attributed to the stabilization of the sensor or the equilibration period for the soil-water-sensor system. Most of the profiles of suction versus depth indicate the classical shape of curve to one degree or another with higher suction near the surface and then decreasing with depth. This can be seen on the plots of suction versus depth for the Agwatronics sensors included in this report. Also of note is the variation in suction versus time. This variation cannot be adequately explained at this stage due to uncertainties with the initial manual readout device manufactured by Agwatronics of California. At present it is not known if the fluctuation in suction is related to thermal variations of the readout device itself. These questions should be resolved when a sufficient data base has been established with the aid of the data acquisition system allowing more frequent measurements. This system will allow the temperature of the sensor tip to be measured prior to obtaining a suction measurement.

5.3 PROBLEMS IDENTIFIED AND RESOLVED TO DATE

5.3.1 FILTER PAPER

There were several problems identified with this method over the course of this study. Some of the problems have been discussed but will be readdressed for clarity. One of the major problems associated with this difficulty arising out of the inability of measuring matric suction consistently. As previously discussed, this problem became evident when attempts to measure matric suction resulted in the measurement of total suction. It is speculated that this phenomenon is caused when matric determinations are attempted on samples with insufficient pore fluid for the fluid to flow into the filter paper in the fluid phase. It is also possible that there are further interactions betweeen the filter paper, soil and pore fluid that are currently not understood and that further contribute to this phenomenon. The net result is that when matric suction measurements are attempted using this method, total suctions are frequently obtained. It is not always possible to ascertain if a given measurement is matric, total suction or in some state of flux between the two.

It is also a possibility that if a longer period of time were allowed for equilibration, this problem would be further reduced. Currently, as stated in the literature, it is felt that equilibration times of three to seven days are sufficient. A minimum of seven days for equilibration was used for this study.

Adding to these difficulties were procedural problems experienced with this method. These problems arose out of the extremely small measurements required for water content determinations. Typically a filter paper will weigh in the order of 0.25 g. Typical water contents encountered for the suction values determined were in the range of 30 to 60 percent. This then requires the measurement of extremely small quantities of water. After the filter paper has equilibrated next to the soil sample for the required period, the filter paper must be removed from the sample and the initial wet weight determined. The instant the filter paper is removed from the soil the atmosphere exerts a relatively large suction on the water within the filter paper. The water instantly begins to evaporate. This results in the wet weight of the filter paper changing constantly. This problem also occurs to a lesser extent after the filter paper is oven dried and the dry weight is to be determined. The problem is directly related to the magnitude of the relative humidity of the atmosphere as compared to the suction within the filter paper. With the humidity in the laboratory virtually always being different from that required for equilibrium in the filter paper, a weight change always occurs. It was also noted that the tare containers used in water content determinations gained and lost weight as they gained water from and lost water to the filters papers. The

net combined effect of these difficulties is that this method is technique sensitive.

Various procedural techniques were employed in an attempt to minimize the effects of some of the difficulties discussed. Efforts were made to reduce the time of handling of the wet papers prior to weighing to a matter of seconds. This reduced the total magnitude of loss although the rate of loss remained the same. Similar procedures were invoked for the dry weight determinations. The problems related to the total suction being measured when attempting to measure matric suction has not been resolved. The measurement of total suction worked well in almost all cases and it is possible that this method is better suited for this type of measurement.

5.3.2 PSYCHROMETER

The procedures are slightly more involved and the equipment costs are significantly greater with this method as opposed to the filter paper method. There were no major difficulties associated with the calibration or testing conducted with this method. The only difficulty of note is that posed by the high sensitivity of the psychrometer and the readout device to the existence of minute thermal gradients experienced in the laboratory. To overcome this difficulty, the sample and the psychrometer are enclosed within a small chamber. The chamber itself is then submerged in a multi-layered water bath. The bath temperature is maintained to within plus or minus 0.01 degrees Celcius.

After the psychrometers have been calibrated, the time required for each suction measurement was in the order of two to three days. For all sites, except Site No. 4, the data collected agreed quite closely with the expected values and the values of total suction as detemined by the filter paper method. Most of the discrepancies can be attributed to the occasional spike or drop in suction value associated with agreeement of this method to the other systems is related to the uncertainty of the systems to which it has been compared.

This equipment has been in existence for several years, has proven reliability and is readily obtainable. These facts combined with the high repeatability of calibration and test results obtained would indicate a more reliable system than the filter paper method.

5.3.3 AGWATRONICS MOISTURE STRESS SENSORS

The Agwa II moisture sensors are supplied by Agwatronics Inc. of Merced, California. This company is a small, specialized firm. Agwatronics designs and builds the sensors. The manual readout device and the sensor interface and power supply for the data logger were designed and built for Agwatronics by third party developers. The

manual readout device and the sensor interface and power supply are new products but the sensors have been in existence for several years. The sensors to date have been used primarily in the irrigation industry to control automated irrigation systems. The sensors are proven devices and no difficulties were experienced with them.

The system was essentially plagued with minor technical difficulties and setbacks throughout the project. The problems included electronic incompatibility of the manual readout device with the data logger as well as power supply difficulties with the sensor interface/power supply for the data logger. The electronic incompatibility of the manual system and the data acquisition system was manifested as a shift in the calibration of the original sensors. The net result was that a negative suction or positive pressure for some of the sensors was measured at times. This became less noticeable with time as the suctions increased, however, the offset difficulty was found to exist with the manual readout device and not with the Bench-model data logger used by Agwatronics. It was subsequently determined that the calibration equations for the sensors were incorrect for the manual readout device. The incorrect calibrations resulted in the entire calibration curve being offset approximately 50 kPa. The sensors read by the manual readout device would indicate a suction of 50 kPa lower than actual. Some of the sensors were recalibrated by the manufacturer and it was established that this was indeed the case. This difficulty was resolved in three ways. First, when the data acquisition system was purchased for this project, this problem no longer existed since the data acquisition system is based on the same bench-model system used by Agwatronics for sensor calibration. Secondly, the supplier agreed to exchange the manual device for an updated model with this problem rectified. Finally, the offset was to be established by running the original manual readout device and the new data logger in parallel to establish the correction for the data already collected. At this time the exact magnitude of the offset is still to be established.

The major difficulty with the sensor interface and the power supply for the data acquisition system is that the third party developer had erroneously made the device with a 110 volt A.C. power supply instead of the required 12 volt D.C. Initially it was thought that a voltage inverter could be used to convert 12 volt D.C. to 110 volt A.C. This essentially worked but the operation of the voltage inverter itself caused a relatively large power drain on the system. This greatly reduced the operational life of the batteries which subsequently reduced the duration of unattended data collection. Further to this, it was established that the sensor wiring harness as designed for the 110 volt supply was inadequate and required modifications for 12 volt D.C. operation. The sensor interface and power supply was returned for exchange. Although these are not directly related to measurement of matric suction, it typifies many of the seemingly daily minor delays

and setbacks experienced in the development of this system. Many of these difficulties can be related to the fact that we received some of the first production models of this equipment complete with the inherent difficulties associated with being the first user of any prototype.

5.4 PRELIMINARY CONCLUSIONS AND APPLICABILITY OF RESULTS

The results of this study indicate that suction can be measured in the field. Reasonable agreement was demonstrated between the field measurements, "expected" and lab results for the clays and fine grained soils tested. All major discrepancies were explainable. The manner in which soil suction in the subgrade varies throughout the season has been partially addressed. However, more data is needed to differentiate between the soil and system response.

Our comments and conclusions regarding the measurement systems tested are as follows:

a) The McQueen and Miller Filter Paper Method theoretically measures matric suction when sufficient contact is established between the filter paper and soil sample. However, we are not able to ensure that sufficiently good contact is made and it was not always possible with the procedures followed here to establish this degree of contact. For reasons associated with this technique sensitivity, it is proposed that this method not be used for the determination of matric suction.

b) Hamblin's Filter Paper Method theoretically measures matric suction when in good contact with the soil. The problems experienced with degree of contact, as discussed above also apply to this method. Further to this problem, there was difficulty with the calibration of the filter papers used in the original published work. A correction was supplied by the author but some difficulties still remained. Therefore, given that the calibration problems could be fully resolved, and the similarity of this method to the method above, it has been essentially dropped as an alternative.

c) The Miller and Branson Paper Method is similar to the McQueen and Miller method with the major difference being in the degree of contact. This method uses no contact between the filter paper and the soil sample. No difficulty was experienced with establishing this degree of contact. A fair degree of confidence is attributed to this method and as such this method may be used as a laboratory procedure for the determination of total suction.

d) The Psychrometer Method measures total suction. This method worked well but is sensitive to the thermal environment in which the test is conducted and is operator sensitive. It is our opinion that it may be employed in measurement of total suction in the laboratory.

e) The In Situ Agwatronics Method has had several difficulties mainly related to supply of equipment and some minor technical difficulties which have been addressed. Many of the difficulties experienced with this method have been resolved and the few remaining problems essentially have been resolved.

Although this method has had considerable development related difficulties, it is still the preferred method for several reasons. First, the method demonstrates good, relatively consistent results. Secondly, this method measures matric suction directly and as such no estimate or measurement of osmotic suction is required. Measurement of osmotic suction is required with the total suction methods in order to reduce measurements to matric suction. Thirdly, the system lends itself to data acquisition and battery operation which is essential for field measurement at remote locations.

It is our opinion that field suction measurement can be applied to existing theory of subgrade performance and slope stability, however, more data would be required to confirm this preliminary judgement.

5.5 FUTURE WORK

The main items which remain to be addressed include the demonstration of the manner in which soil suction in the subgrade varies throughout a season. Continued monitoring of the Agwatronics moisture stress sensors is needed in order to compile a sufficient data base to firmly establish this. Additional funding will be sought in order to facilitate the continued monitoring of these installations and at the same time extend the field testing of this system.

More specifically with regards to the Agwatronics system:

1) The system measures suction but electro-mechanical network improvements are needed to enhance reliability and enable this equipment to be left unattended in remote sites as well as to make measurements more economical to obtain.

2) Delays in the supply of hardware prevented measurement through freeze-thaw cycles. Readings should be continued through a complete seasonal cycle with the improved equipment.

3) Progress has been made in removing the differential in readings with the portable versus bench reading units. Additional field data are required to confirm reliability of the portable system.

4) When repeatability and reliability of suction measurements has been demonstrated, research should be continued into the appropriate means of incorporating this parameter into subgrade support and slope stability models (Phases 2 and 3 of research program).

In summary, this work has made substantial progress into field measurement of matric suction. The results are positive with some difficulties left to be resolved.

At this stage, it appears that direct measurement is possible allowing existing theory to be utilized in geotechnical analysis. However, additional effort should be invested to collect additional field data to further test, and create confidence in the measuring system.

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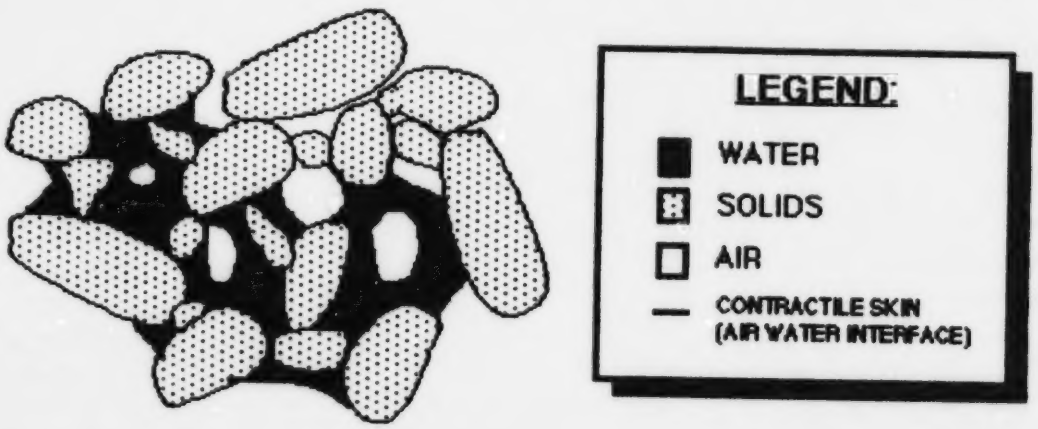


Figure 1: Schematic Phase Diagram For Unsaturated Soils

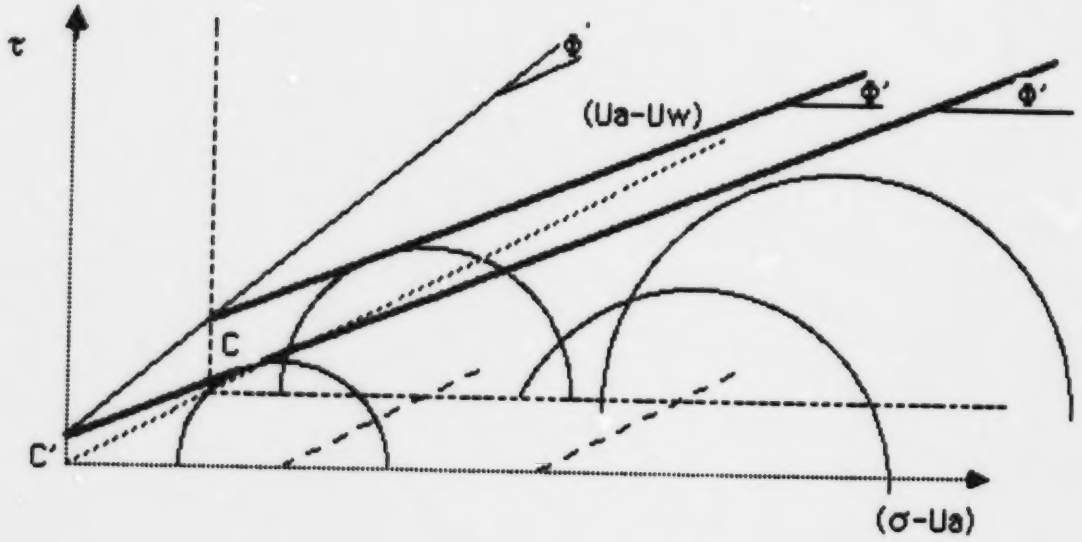


Figure 2. Three Dimensional Failure Surface Using Stress Variables Using (σ-ua) And (Ua-uw) - (After Ho And Fredlund 1982).

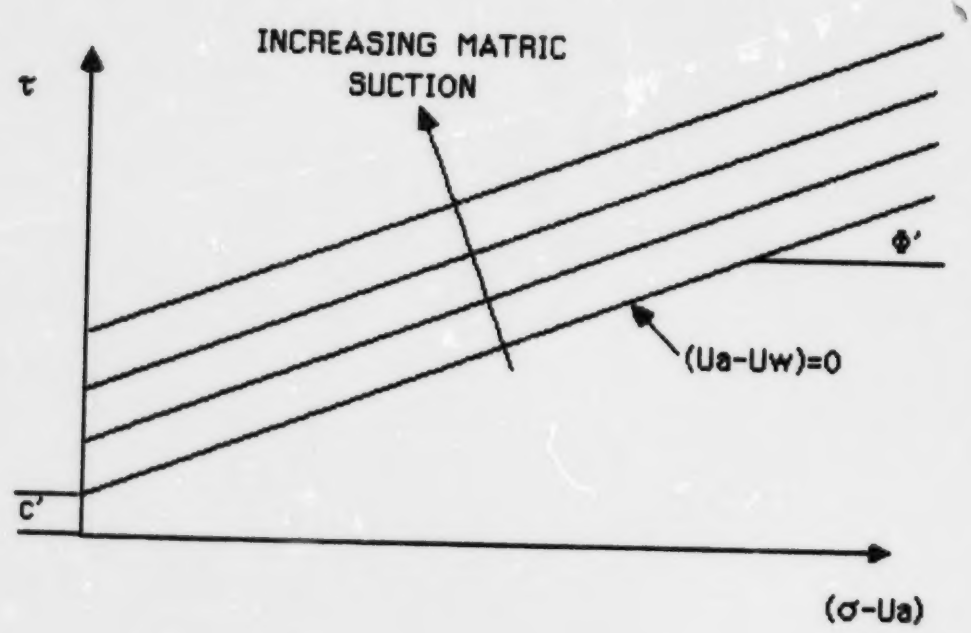


Figure 3: Failure Surface Of An Unsaturated Soil Looking Parallel To The (Ua-uw) Axis. (After Ho And Fredlund 1982)

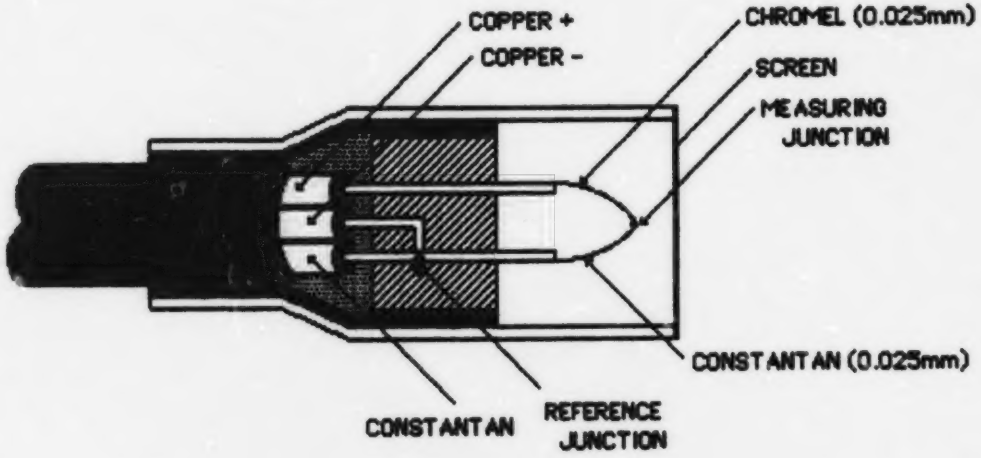
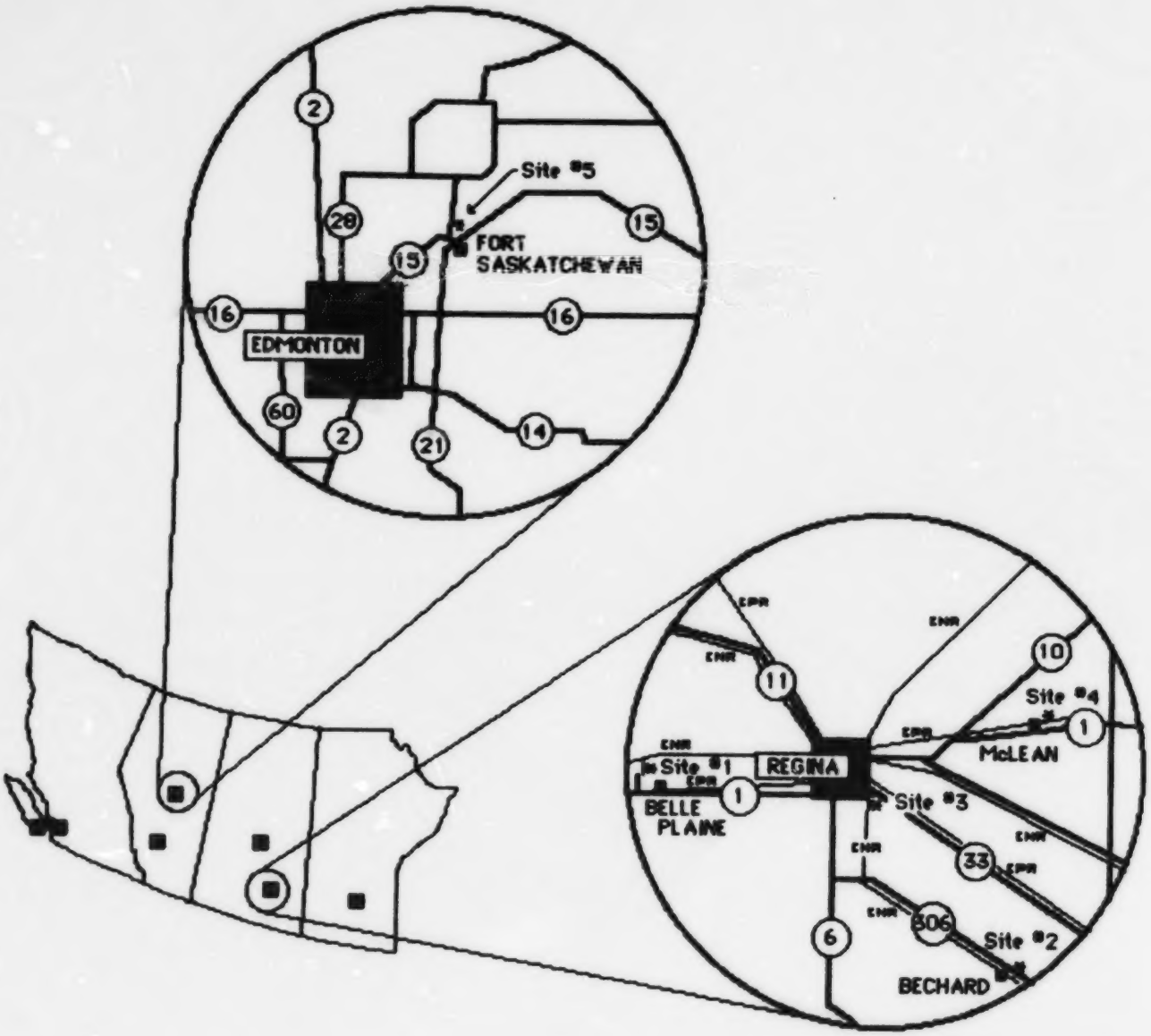
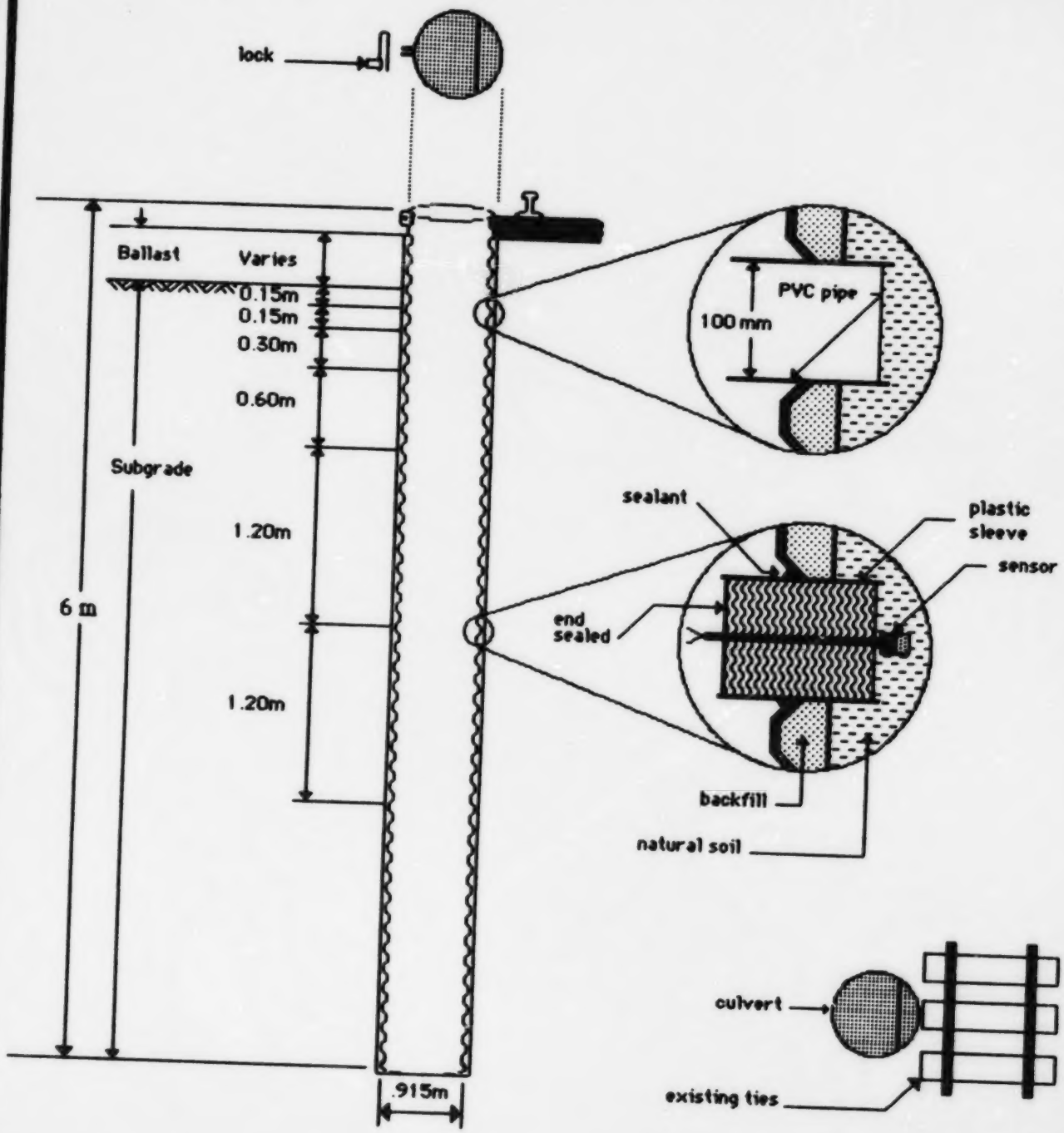


Figure 4: Detail Of A Typical Thermocouple Psychrometer



SCALE: NTS

FIGURE 5 : PLAN SHOWING LOCATION OF SITES IN WESTERN CANADA



CLIFTON ASSOCIATES LTD REGINA SASKATOON CONSULTING GEOTECHNICAL ENGINEERS	CLIENT CP/CN/M.O.T.		
	TITLE TYPICAL CULVERT INSTALLATION DETAILS		
	APPROVED PvdR	DATE 84/11/01	FIGURE 6

TEST HOLE LOG

SHEAR STRENGTH:
■ unconfined
□ pocket pen
✕ lab vane

SHEAR STRENGTH -KPa
50 | 100 | 150 | 200

▲ DRY DENSITY g/cm³
1.3 | 1.5 | 1.7 | 1.9 | 2.1

P.L. NM L.L.
10 30 50 70 90%

DATE 84/09/10 HOLE NO. 1-1
GROUND ELEV. _____
LOCATION MILE 24.3 CB01

DEPTH m	NO. TYPE	UNIF P.I.	N
1		CH 41.1	
		MH-OH 37.2	
2		CH 39.9	
		CH 46.8	
3		CH 45.7	
		CH 53.9	
4		CH 58.3	
		CH 44.8	
5		CH 38.7	
		CH 56.6	
6		CH 50.6	
		CH 39.7	
7		CL 22.7	
		CL 18.9	
8		CL 20.2	
		CL 23.2	
9		CL 22.2	
10			

SYMBOL

DESCRIPTION OF MATERIALS

BALLAST - gravel, clean
0.46m — - dry to damp

CLAY - highly plastic
- olive (5Y 4/4), oxidized
- laminated
- stiff to very stiff
- silty at 1.98m and 3.96m
- occasional silt pockets and silter laminations throughout
- slight organic odour noted at 2.3m depth
- Fe and Mn stains noted along laminations

6.1m

TILL - sandy clay matrix
- olive (5Y 4/4) becoming dark greyish brown (2.5Y 4/2) below 6.9m
- oxidized
- damp to moist
- very stiff to hard
- jointed with Fe stains along joints below 6.9m

9.45m — end of hole

NOTE:
+ Indicates location of eqwatronics moisture sress sensors

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REGINA
SASKATOON

PROJECT ENGINEERING RESEARCH
LOCATION BELLE PLAINE, SASKATCHEWAN
PROJECT NO. R461 FIGURE NO. 7

PIEZOMETER CONSTRUCTION DETAILS

DEPTH m	SOIL DESCRIPTION	ELEV. m
0		100.0
	BALLAST - GRAVEL	99.54
1	CLAY	
2		
3		
4		
5		
6		
7		93.90
	TILL	
8		
9		90.55
10		

PIEZOMETER NO. 1-1
TEST HOLE NO. 1-1

LOCATION MILE 24.3 CB01
BELLE PLAINE
SASKATCHEWAN

TOP PIPE ELEV. 100.3m
GROUND ELEV. 100.0m
BASE SCREEN ELEV. 90.86m
TYPE OF PIPE 50mm Ø PVC

TYPE OF SCREEN 50 mm Ø RICE
#10 SLOT
TEST HOLE DIA. 125 mm Ø
INST. DATE 84/09/10
TECHNICIAN PvdR
CONTRACTOR PROBE
DRILL BRATT 22

WATER LEVELS

DATE	TIME	DEPTH - m	ELEV. - m
/09/10	-	-	DRY
/11/07	-	-	DRY
/12/06	-	-	DRY

REMARKS

All elevations referenced to top of tie.
Top of tie elevation assumed 100.0m.

MATERIALS:
- CUTTINGS
- BENTONITE PELLETS
- 10/20 SILICA SAND

DRAWN BY: PvdR
APPROVED BY: PvdR

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REGINA
SASKATOON

PROJECT ENGINEERING RESEARCH
LOCATION BELLE PLAINE, SASKATCHEWAN
PROJECT NO. R461 FIGURE NO. 8

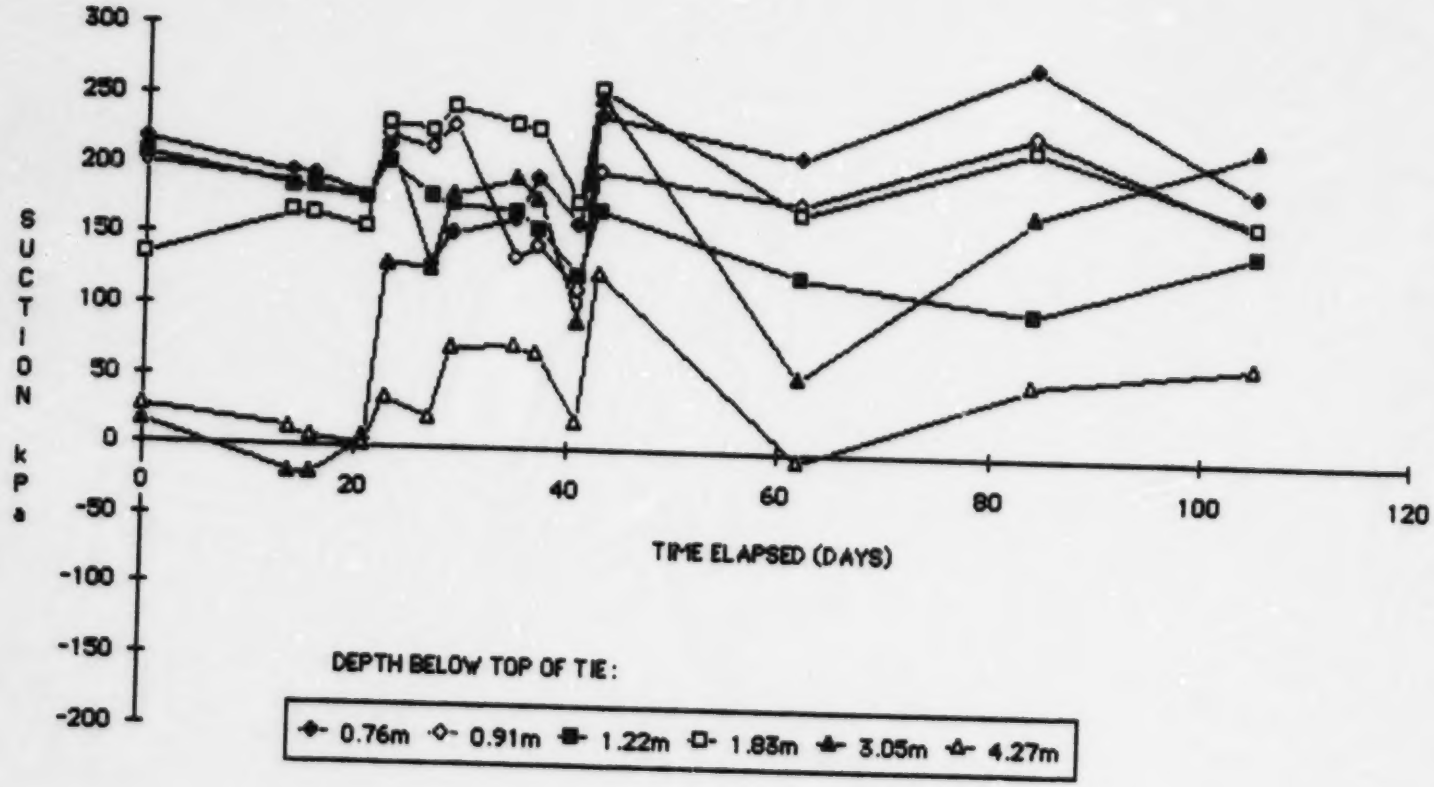


FIGURE 9 : PLOT OF SUCTION VERSUS ELAPSED TIME FOR AGWATRONICS MOISTURE STRESS SENSORS - SITE #1

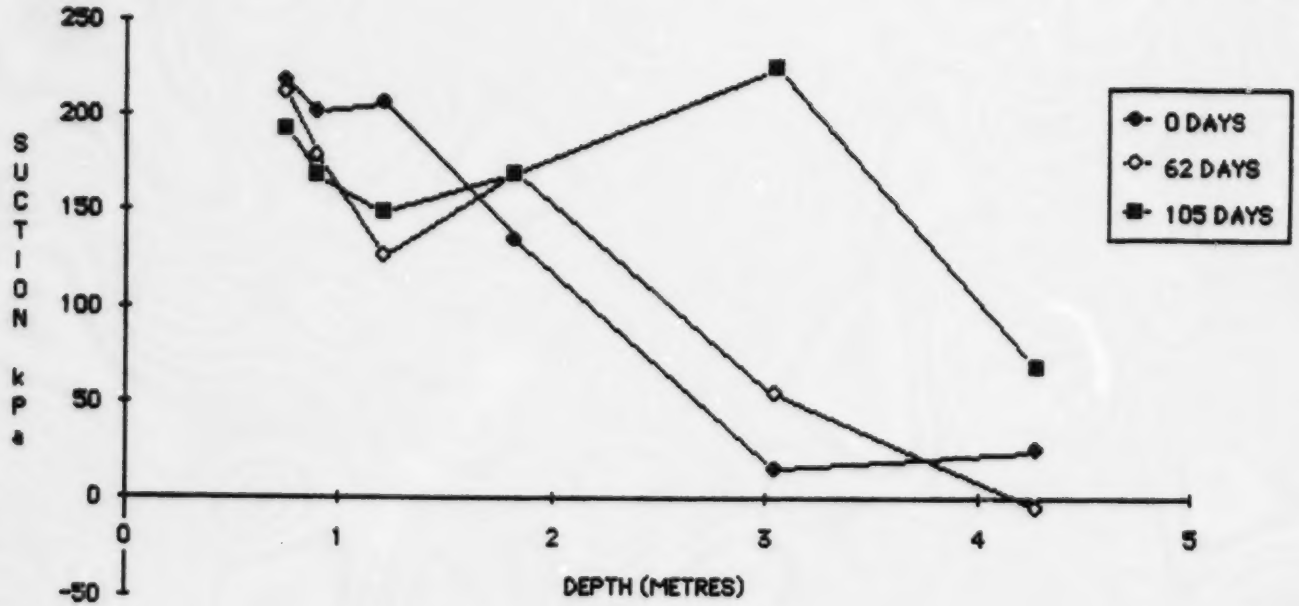


FIGURE 10 : PLOT OF MATRIC SUCTION VERSUS DEPTH AS DETERMINED BY AGWATRONICS MOISTURE STRESS SENSORS - SITE #1

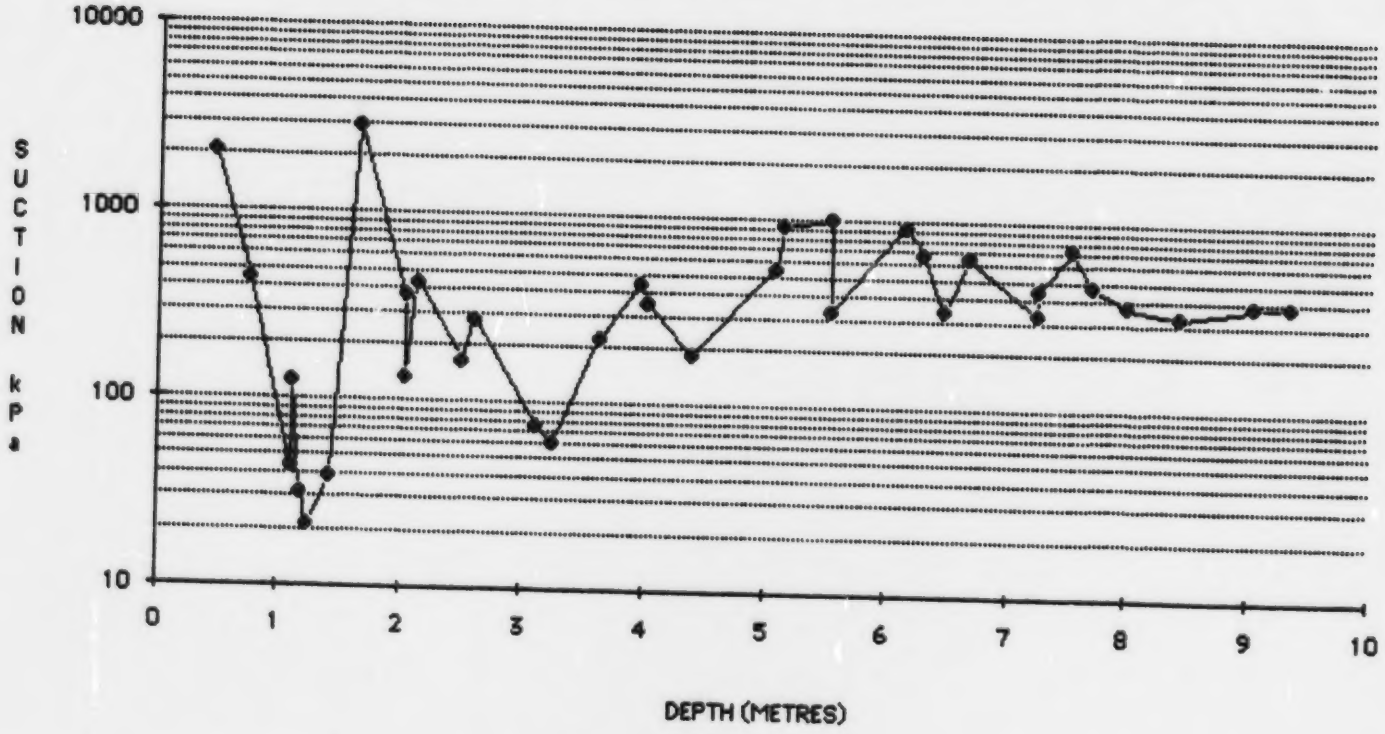


FIGURE 11 : MATRIC SUCTION VERSUS DEPTH FOR TEST HOLE 1-1 BY THE McQUEEN AND MILLER FILTER PAPER METHOD

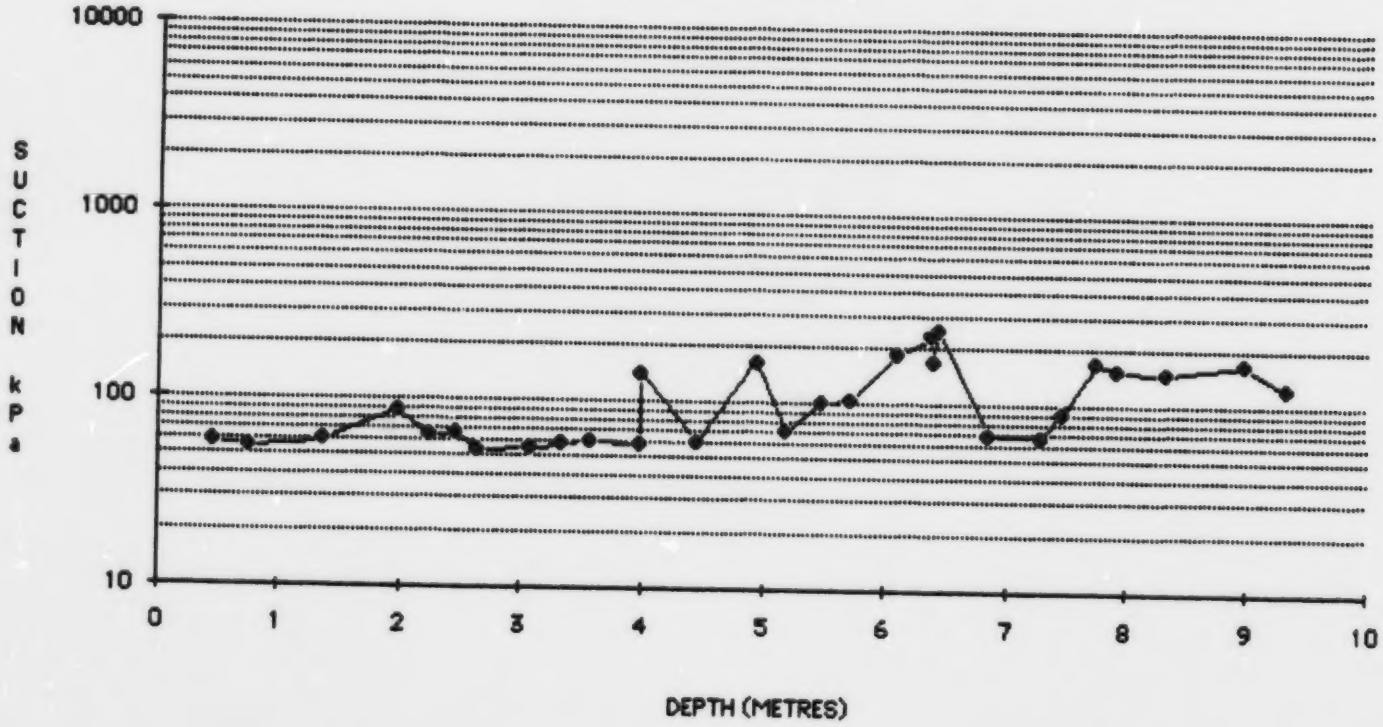


FIGURE 12 : MATRIC SUCTION VERSUS DEPTH FOR TEST HOLE 1-1 by HAMBLIN'S METHOD
(AFTER FAWCETT AND COLLIS-GEORGE 1967)

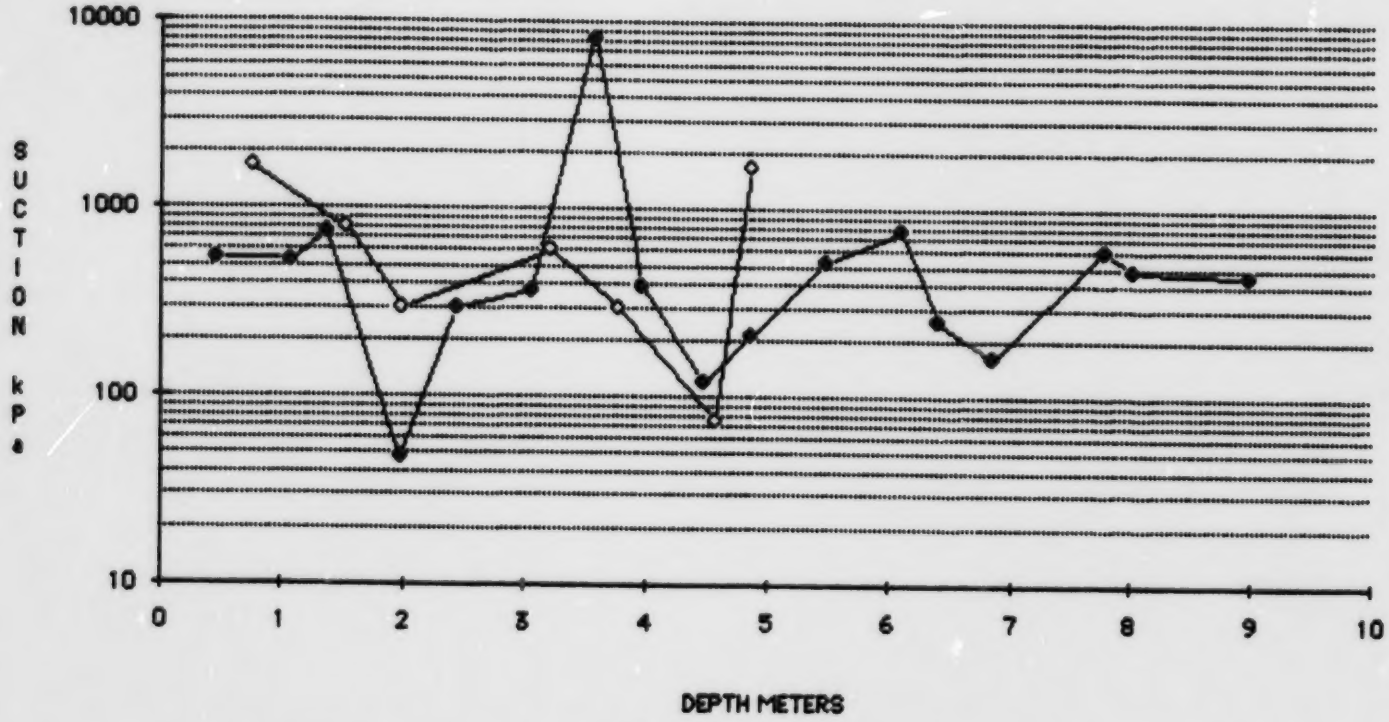


FIGURE 13: TOTAL SUCTION VERSUS DEPTH FOR TEST HOLE 1-1 AFTER THE McQUEEN AND MILLER FILTER PAPER METHOD (NO CONTACT)

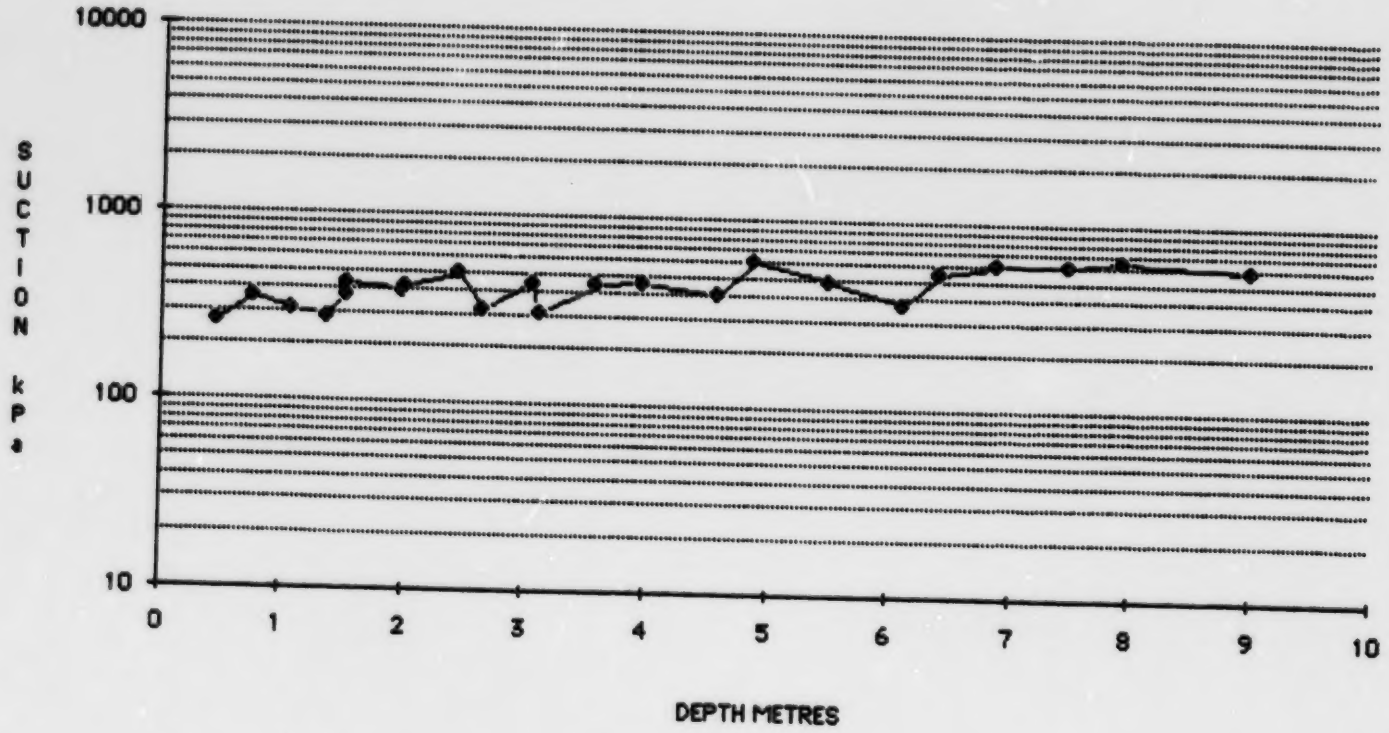


FIGURE 14 : PLOT OF TOTAL SUCTION VERSUS DEPTH FOR SITE #1
BY THE PSYCHROMETER METHOD

TEST HOLE LOG

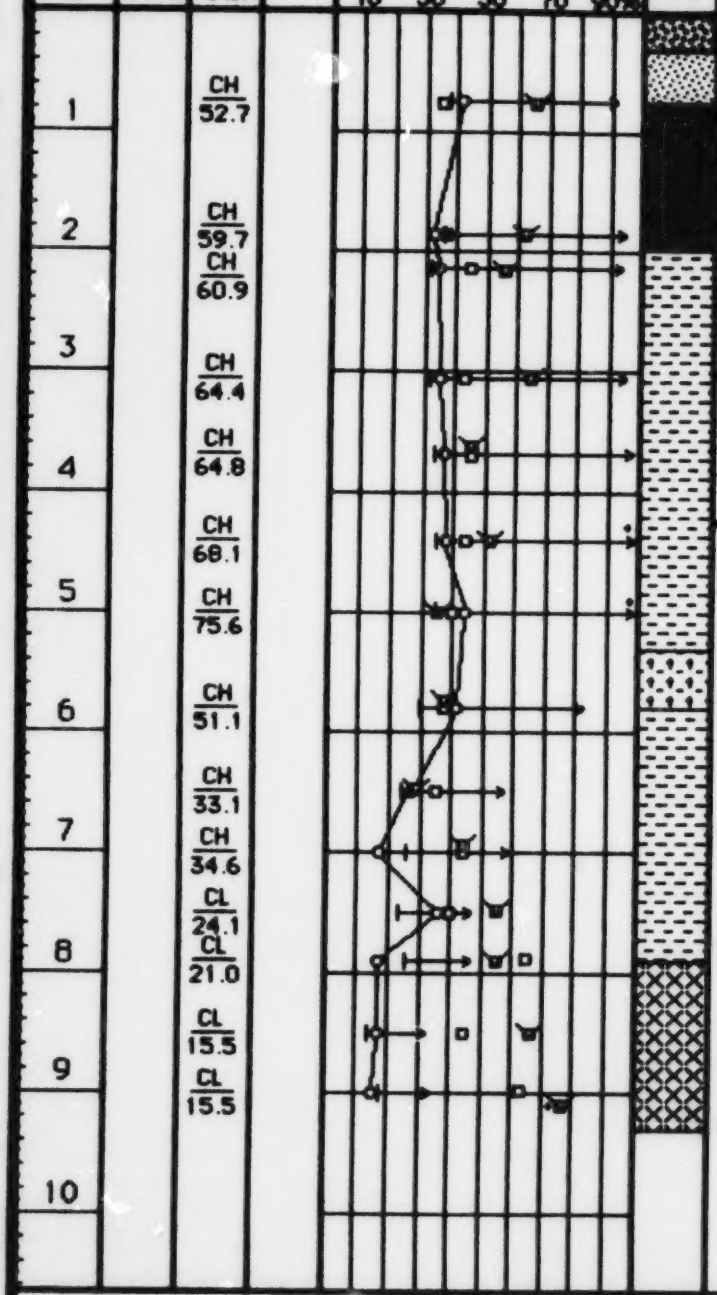
SHEAR STRENGTH:
■ unconfined
□ pocket pen
ᗯ lab vane

SHEAR STRENGTH -KPa
| 50 | 100 | 150 | 200 |

▲ DRY DENSITY g/cm³
1.3 | 1.5 | 1.7 | 1.9 | 2.1

P.L. — %M — L.L.
10 30 50 70 90%

DATE 84/09/13 HOLE NO. 2-1
GROUND ELEV.
LOCATION MILE 78.3 LEYVAN SUBDIVISION



DESCRIPTION OF MATERIALS

0.3m BALLAST - gravel

SUBBALLAST - sand, clean
0.76m - medium to coarse grained

CLAY - highly plastic
- very dark gray (2.5Y 3/0)
- laminated
1.98m - moist, stiff to very stiff
- organics, rootlets, organic odour

CLAY - highly plastic
- olive (5Y 4/2)
- oxidized
- laminated
- stiff to very stiff
- moist
- silty clay laminations below 3.8m

5.3m

CLAY - medium plastic, silty
5.8m - olive brown (2.5Y 4/4), oxidized
- laminated

CLAY - highly plastic
- olive (5Y 4/2), oxidized
- laminated
- stiff to very stiff
- damp
- till stringers noted from 6.9m to 7.5m

7.9m

TILL - sandy clay matrix
- olive (5Y 4/4) becoming olive brown (2.5Y 4/4) below 9.0m
- oxidized
- very stiff to hard, moist
9.3m - 75mm saturated sand seam noted at 8.2m
end of hole

NOTE:
+ Indicates location of egwatronics moisture sress sensors

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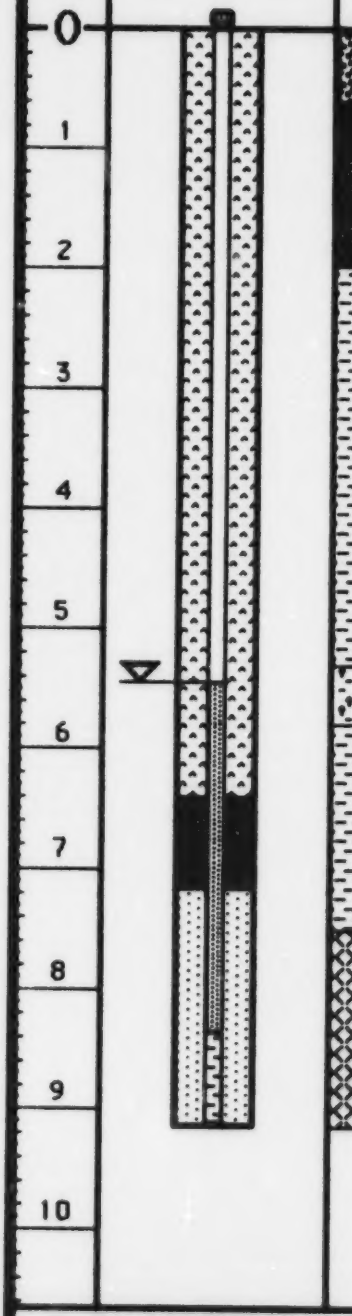
PROJECT ENGINEERING RESEARCH
LOCATION BECHARD, SASKATCHEWAN
PROJECT NO. R461 FIGURE NO. 15

PIEZOMETER CONSTRUCTION DETAILS



SOIL DESCRIPTION	ELEV. m
	100.0
BALLAST -GRAVEL & SAND	99.24
CLAY -HIGHLY PLASTIC -ORGANICS TO 1.98m	
	94.70
CLAY - SILTY	94.20
CLAY - HIGHLY PLASTIC	
	92.10
TILL	
	90.70

PIEZOMETER NO. 2-1
TEST HOLE NO. 2-1

LOCATION MILE 78.3 LEWYAN SUB
BECHARD
SASKATCHEWAN

TOP PIPE ELEV. 100.15m
GROUND ELEV. 100.0m
BASE SCREEN ELEV. 90.86m
TYPE OF PIPE 50mm Ø PVC

TYPE OF SCREEN 50 mm Ø RICE #10 SLOT
TEST HOLE DIA. 125 mm Ø
INST. DATE 84/09/13
TECHNICIAN PvdR /LTN
CONTRACTOR PROBE
DRILL BRATT 22

WATER LEVELS

DATE	TIME	DEPTH - m	ELEV. - m
/09/13	-	-	DRY
/11/08	-	5.58	94.57
/12/07	-	5.50	94.65

REMARKS

All elevations referenced to top of tie.
Top of tie elevation assumed 100.0m.

MATERIALS:
- CUTTINGS
- BENTONITE PELLETS
- 10/20 SILICA SAND

DRAWN BY: PvdR

APPROVED BY: PvdR

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PROJECT ENGINEERING RESEARCH
LOCATION BECHARD, SASKATCHEWAN
PROJECT NO. R461 FIGURE NO. 16

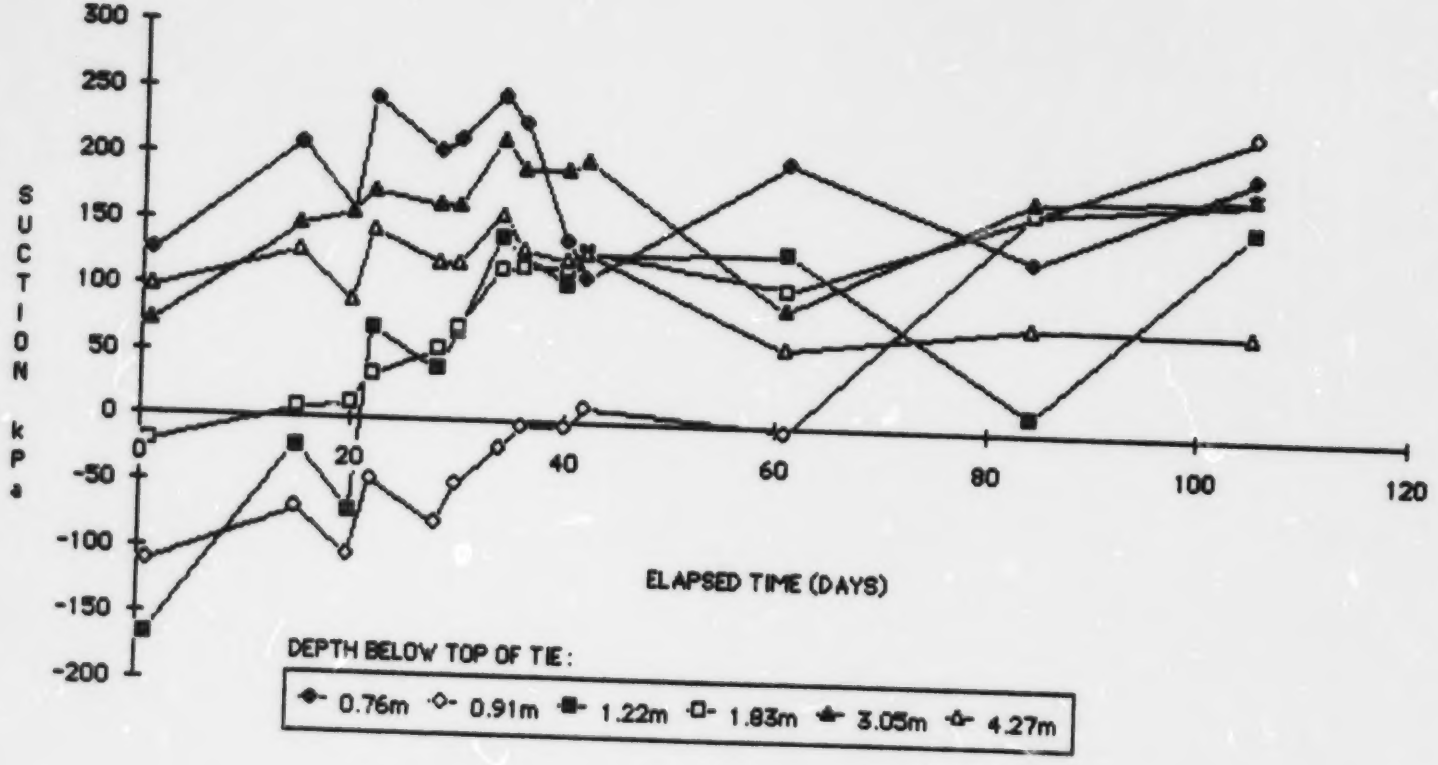

FIGURE 17 : PLOT OF SUCTION VERSUS ELAPSED TIME FOR AGWATRONICS MOISTURE STRESS SENSORS - SITE #2

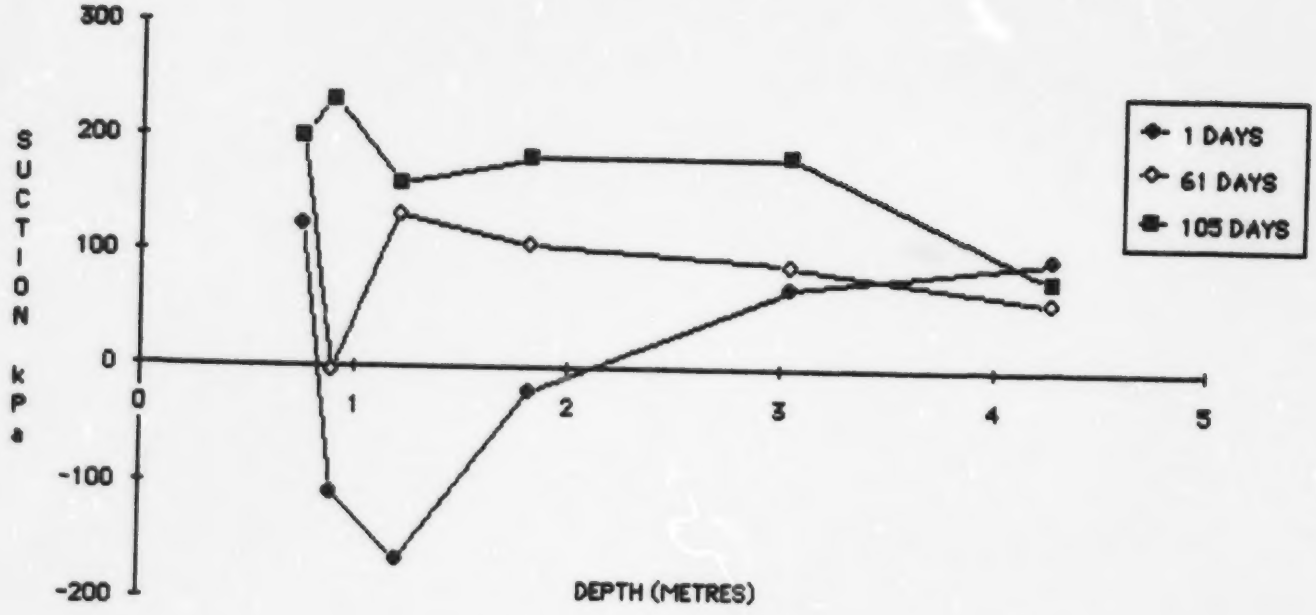

FIGURE 18 : PLOT OF MATRIC SUCTION VERSUS DEPTH AS DETERMINED BY AGWATRONICS MOISTURE STRESS SENSORS - SITE #2

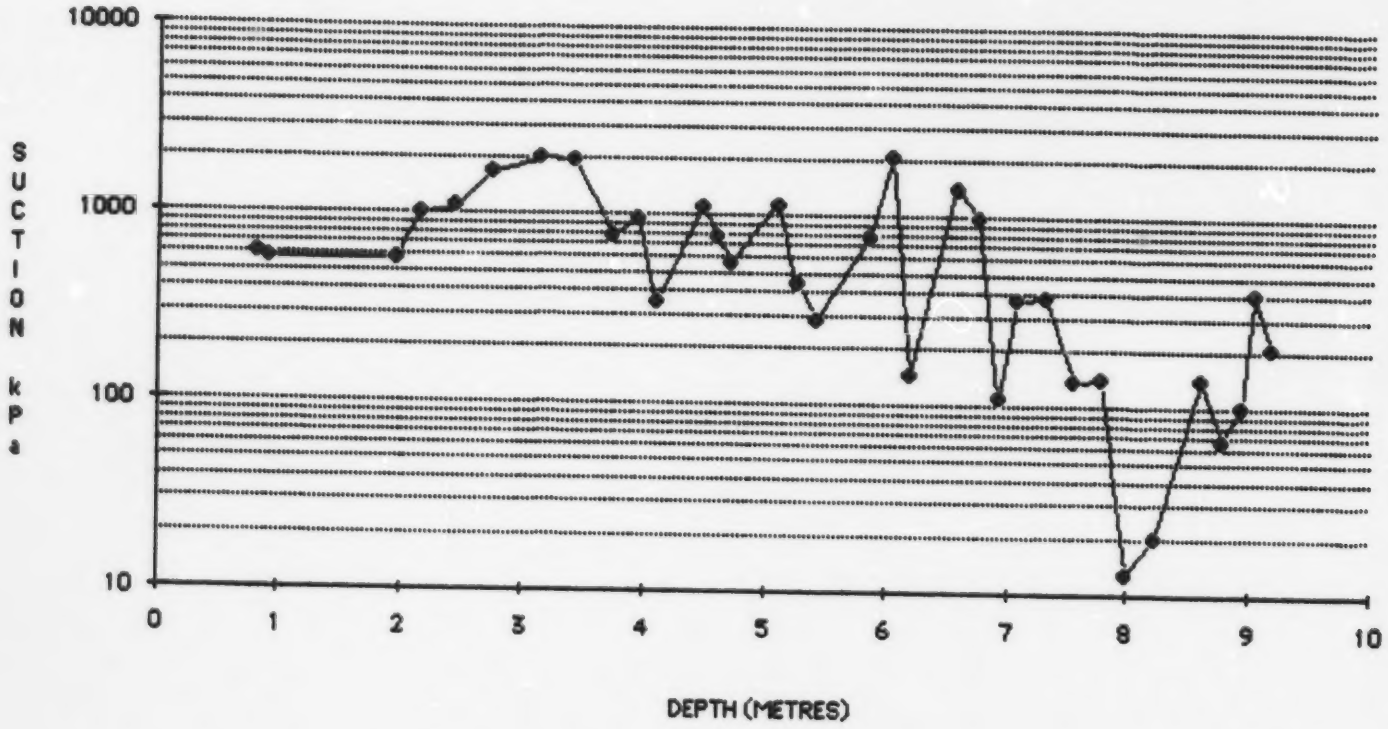

FIGURE 19 : MATRIC SUCTION VERSUS DEPTH FOR TEST HOLE 2-2
BY MCQUEEN AND MILLER FILTER PAPER METHOD

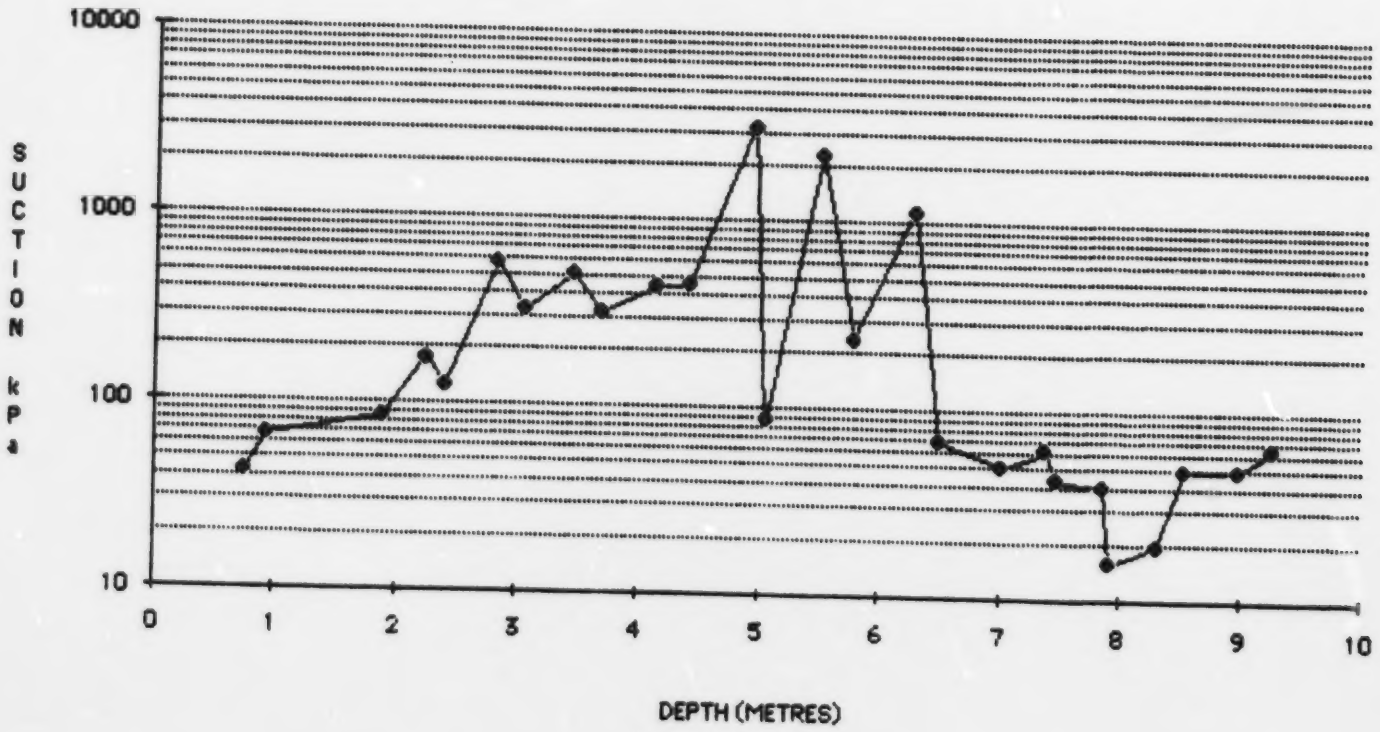

FIGURE 20 : MATRIC SUCTION VERSUS DEPTH FOR TEST HOLE 2-2
BY HAMBLIN'S FILTER PAPER METHOD

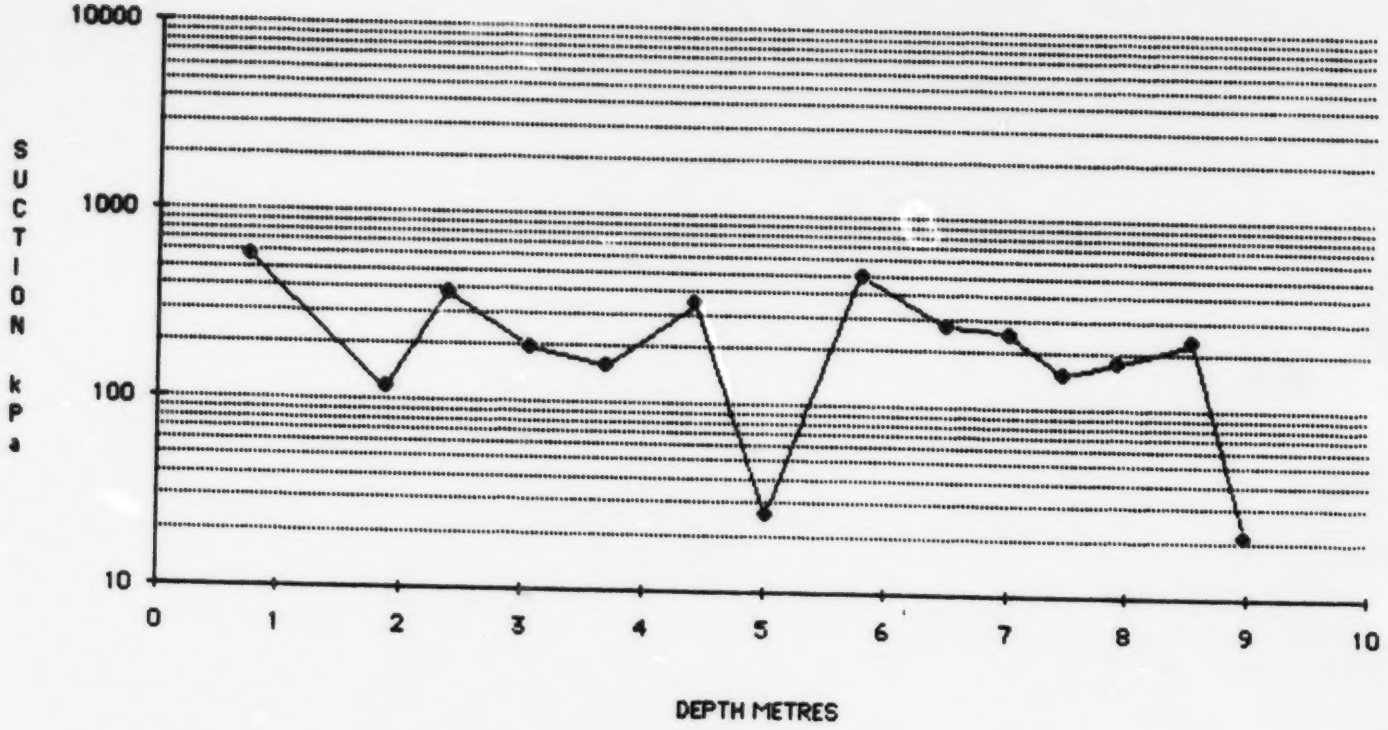

FIGURE 21 : TOTAL SUCTION VERSUS DEPTH FOR TEST HOLE 2-2 AFTER THE McQUEEN AND MILLAR FILTER PAPER METHOD (NO CONTACT)

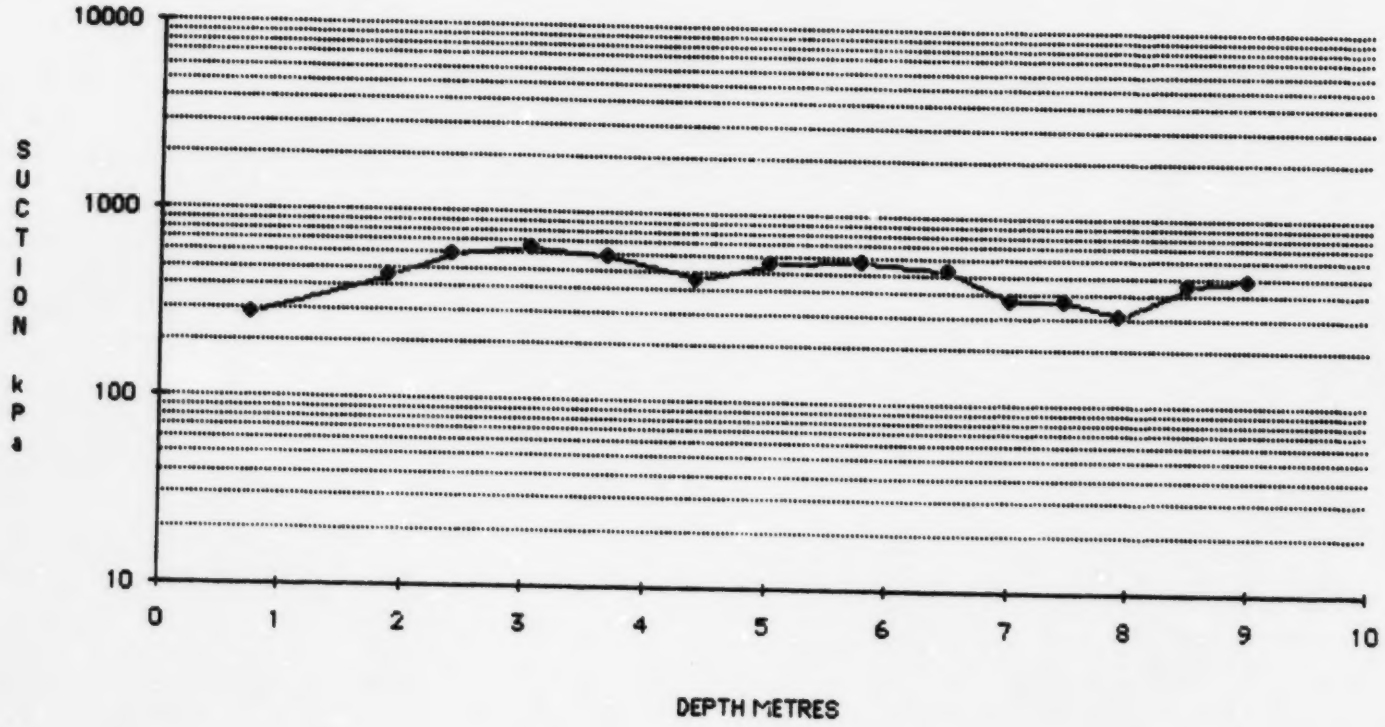

FIGURE 22 : PLOT OF TOTAL SUCTION VERSUS DEPTH FOR SITE #2
BY THE PSYCHROMETER METHOD

TEST HOLE LOG

SHEAR STRENGTH:
■ unconfined
□ pocket pen
⊻ lab vane

SHEAR STRENGTH -KPa
50 | 100 | 150 | 200

▲ DRY DENSITY g/cm³
1.3 | 1.5 | 1.7 | 1.9 | 2.1

P.L. — %M — L.L.
10 30 50 70 90%

DATE 84/09/10 HOLE NO. 3-1
GROUND ELEV.
LOCATION NEW LEWVAN BYPASS

DEPTH m	NO. TYPE	UNIF P.I.	N
1		CH 52.9	
2		CH 71.9	
		CH 58.4	
3		CH 65.7	
		CH 50.5	
4		CH 63.2	
		CH 64.0	
5		CH 67.5	
		CH 68.7	
6		CH 28.1	
		CL 18.2	
7		CL 21.4	
		CL 17.2	
8		CL 18.9	
		CL 17.5	
9		CL 18.3	
		CL 17.3	
10			

SYMBOL

DESCRIPTION OF MATERIALS

BALLAST - gravel

0.46m

CLAY - highly plastic
- dark grayish brown (2.5Y 4/2)
- oxidized
- laminated, mottled
- very stiff to stiff
- damp to moist
- silty clay laminations below 3.4m

5.8m

SILT - clayey
- with highly plastic clay laminations
- olive (5Y 4/2), oxidized
- stiff, moist

6.6m

Till - sandy clay matrix
- medium to stiff
- moist
- Fe stains and salts along micro fissures
- jointed below 8.7m

9.1m – end of hole

NOTE:
✦ Indicates location of aqwatronics moisture sress sensors

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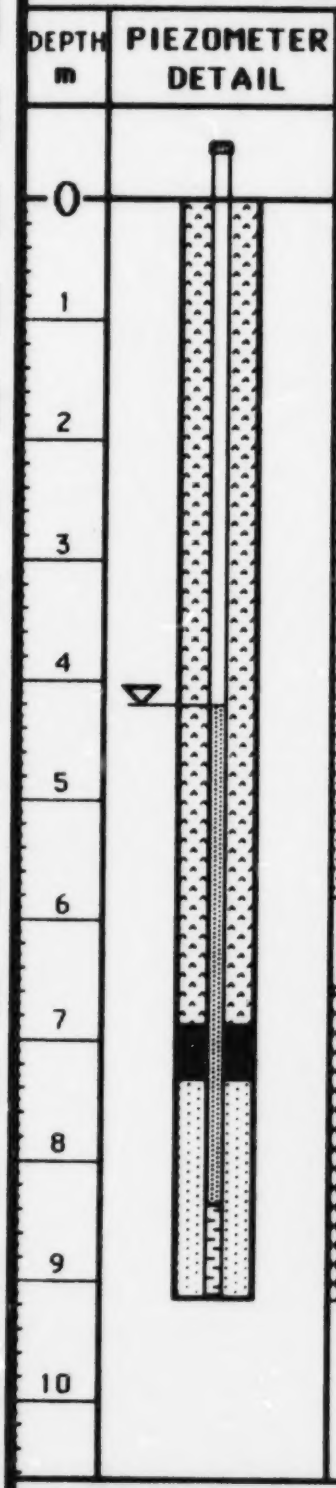
PROJECT ENGINEERING RESEARCH
LOCATION REGINA, SASKATCHEWAN
PROJECT NO. R461 FIGURE NO. 23

PIEZOMETER CONSTRUCTION DETAILS



PIEZOMETER DETAIL	SYMBOL	SOIL DESCRIPTION	ELEV. m
			100.0
		BALLAST - GRAVEL	99.54
		CLAY - HIGHLY PLASTIC	
			94.20
		SILT - CLAYEY	93.40
		TILL	90.90

PIEZOMETER NO. 3-1
TEST HOLE NO. 3-1

LOCATION NEW LEWVAN BYPASS
REGINA
SASKATCHEWAN
TOP PIPE ELEV. 100.46m
GROUND ELEV. 100.0m
BASE SCREEN ELEV. 90.86m
TYPE OF PIPE 50mm Ø PVC
TYPE OF SCREEN 50 mm Ø RICE #10 SLOT
TEST HOLE DIA. 125 mm Ø
INST. DATE 84/09/10
TECHNICIAN PvdR /LTN
CONTRACTOR PROBE
DRILL BRATT 22

WATER LEVELS

DATE	TIME	DEPTH - m	ELEV. - m
/09/10	-	6.70	93.8
/11/08	-	4.66	95.8
/12/07	-	4.70	95.8

REMARKS
All elevations referenced to top of tie.
Top of tie elevation assumed 100.0m.

MATERIALS:
- CUTTINGS
- BENTONITE PELLETS
- 10/20 SILICA SAND

DRAWN BY: PvdR
APPROVED BY: PvdR

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REGINA
SASKATOON

PROJECT ENGINEERING RESEARCH
LOCATION REGINA, SASKATCHEWAN
PROJECT NO. R461 FIGURE NO. 24

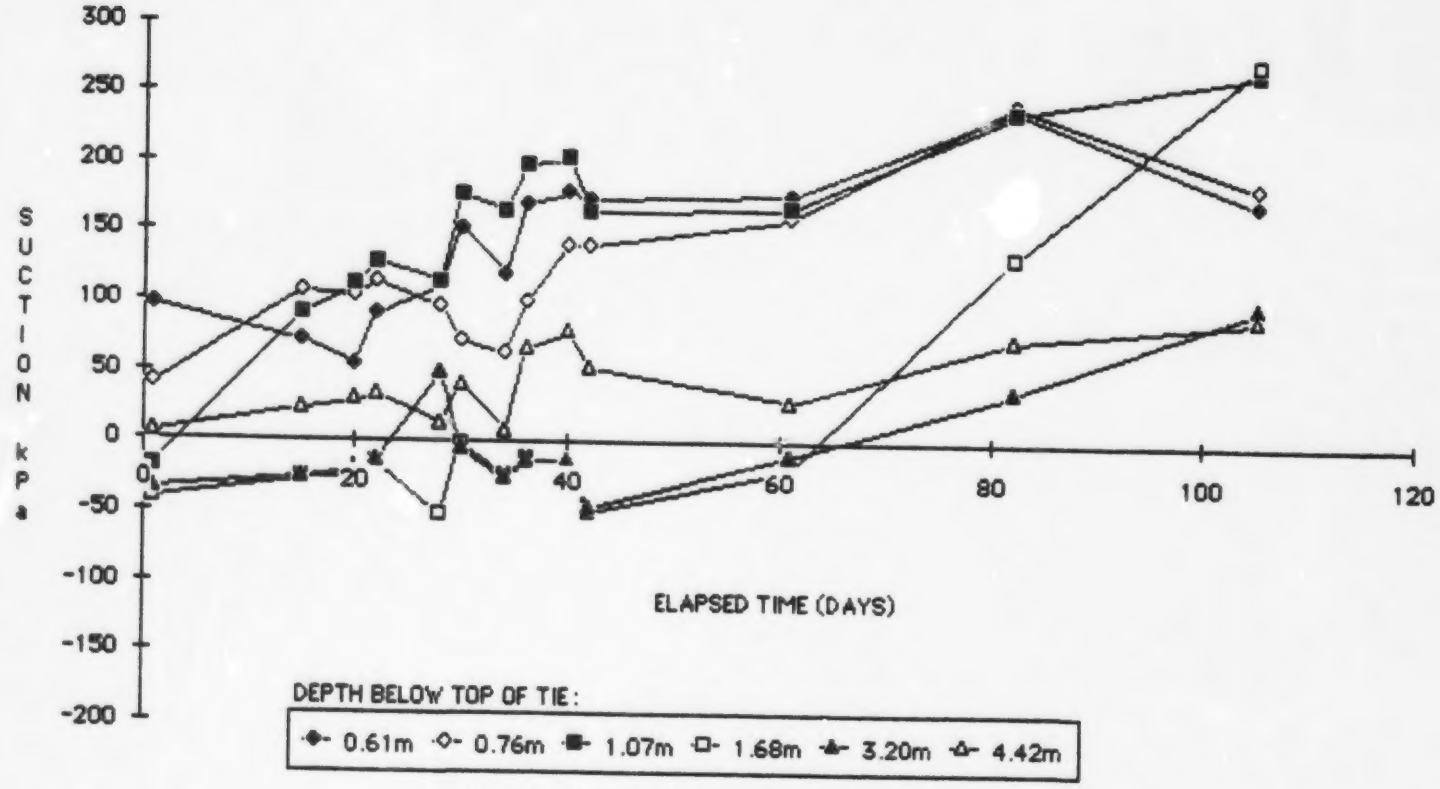


FIGURE 25 : PLOT OF SUCTION VERSUS ELAPSED TIME FOR AGWATRONICS MOISTURE STRESS SENSORS - SITE #3

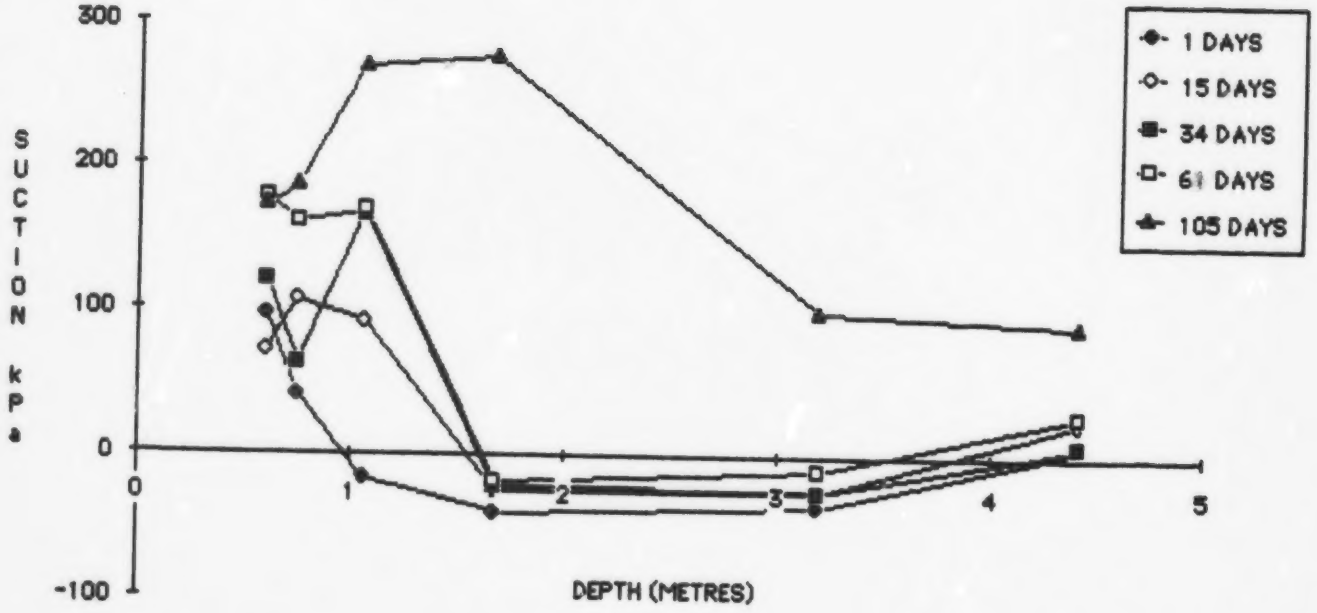


FIGURE 26 : PLOT OF MATRIC SUCTION VERSUS DEPTH AS DETERMINED BY AGWATRONICS MOISTURE STRESS SENSORS - SITE #3

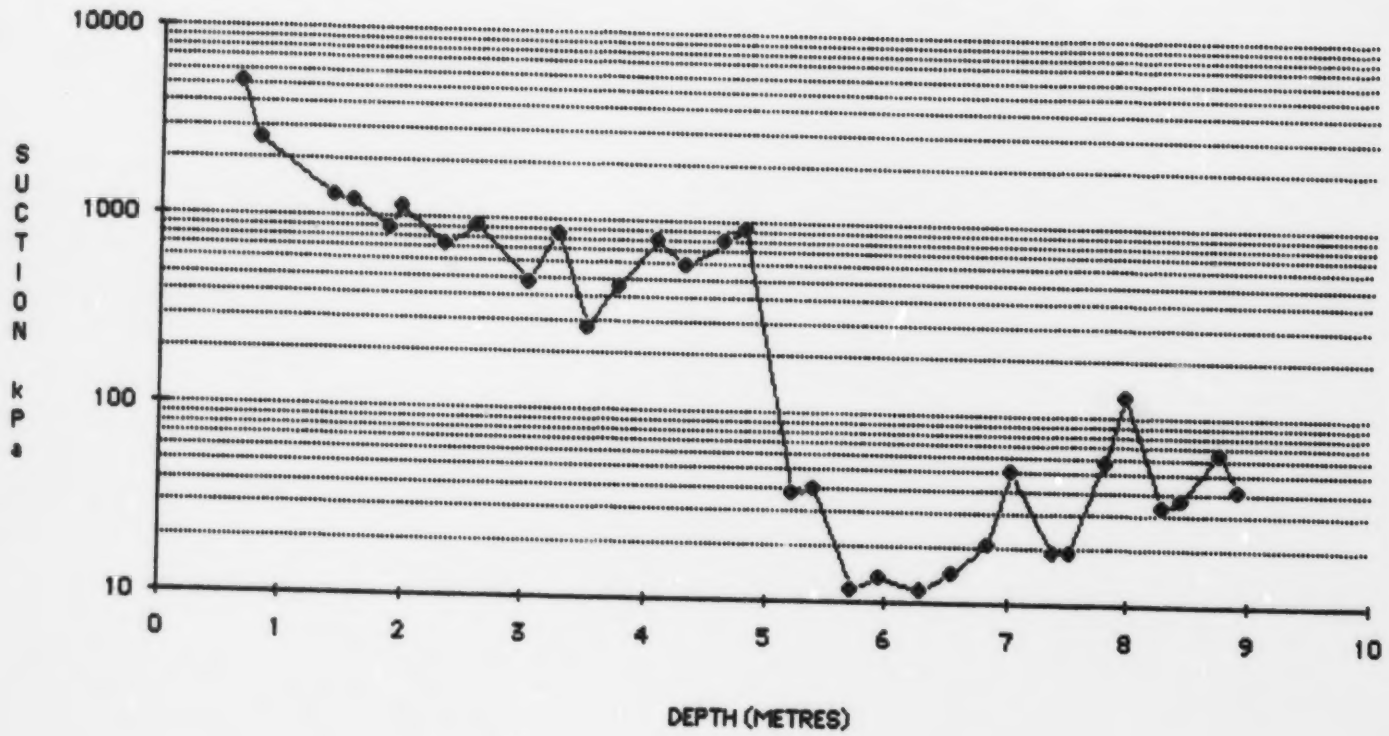


FIGURE 27 : SOIL SUCTION VERSUS DEPTH FOR TEST HOLE 3-2
BY THE McQUEEN AND MILLER FILTER PAPER METHOD

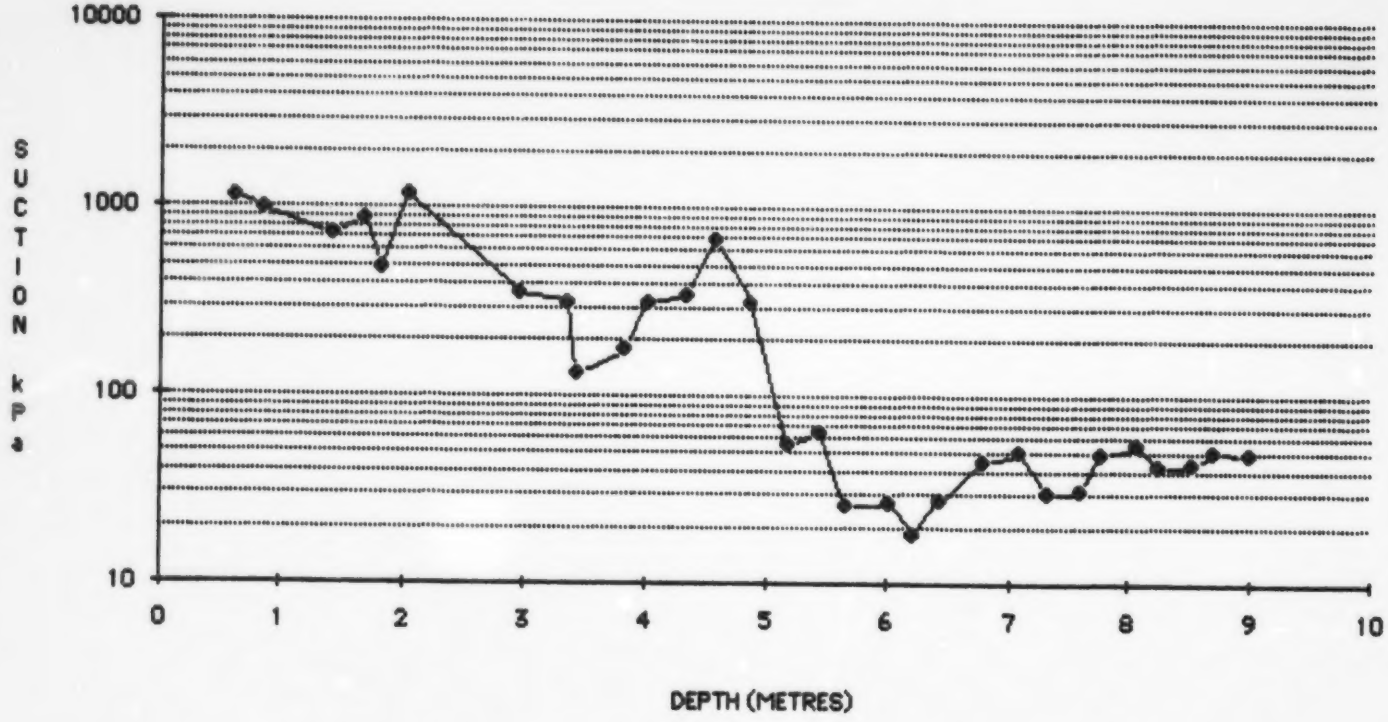


FIGURE 28 : MATRIC SUCTION VERSUS DEPTH FOR TEST HOLE 3-2 BY HAMBLIN'S METHOD
(AFTER FAWCETT AND COLLIS-GEORGE 1967)

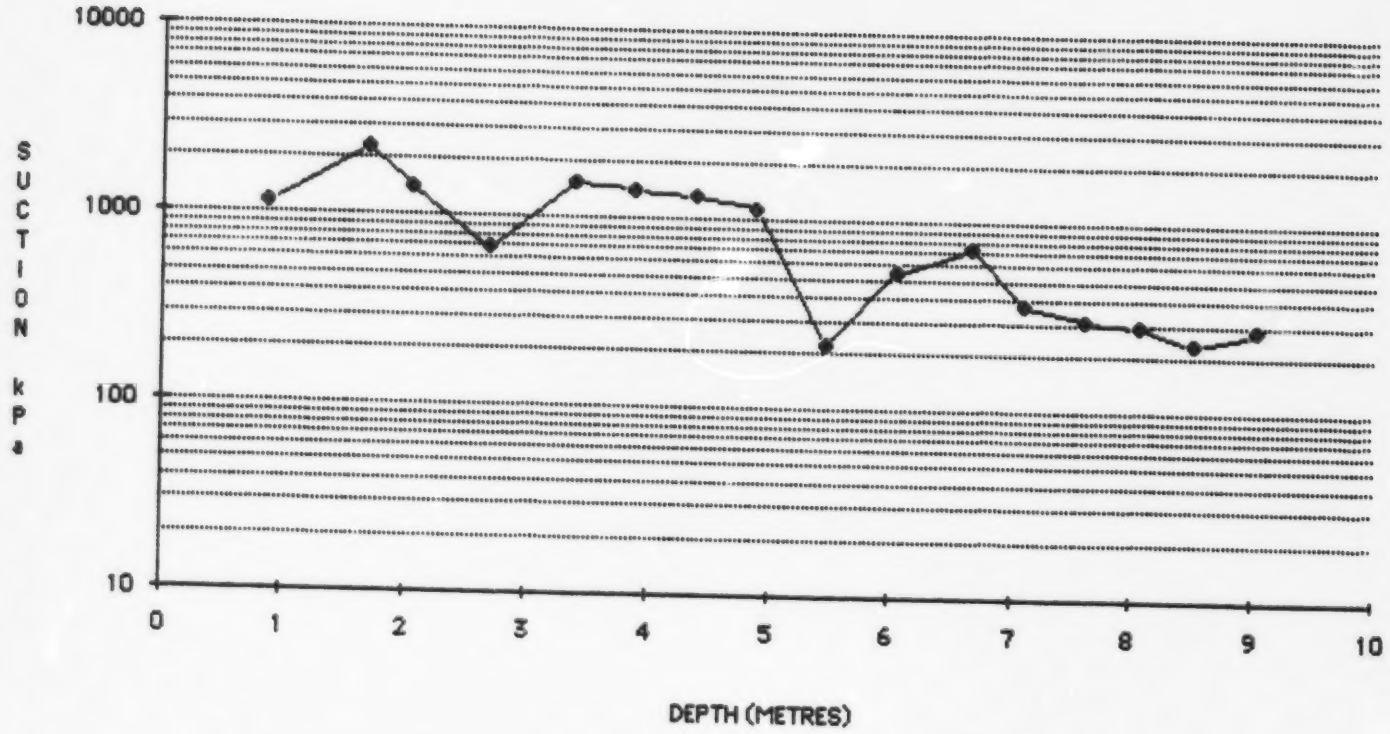


FIGURE 29 : TOTAL SUCTION VERSUS DEPTH FOR TEST HOLE 3-2 BY THE McQUEEN AND MILLER FILTER PAPER METHOD (NO CONTACT)

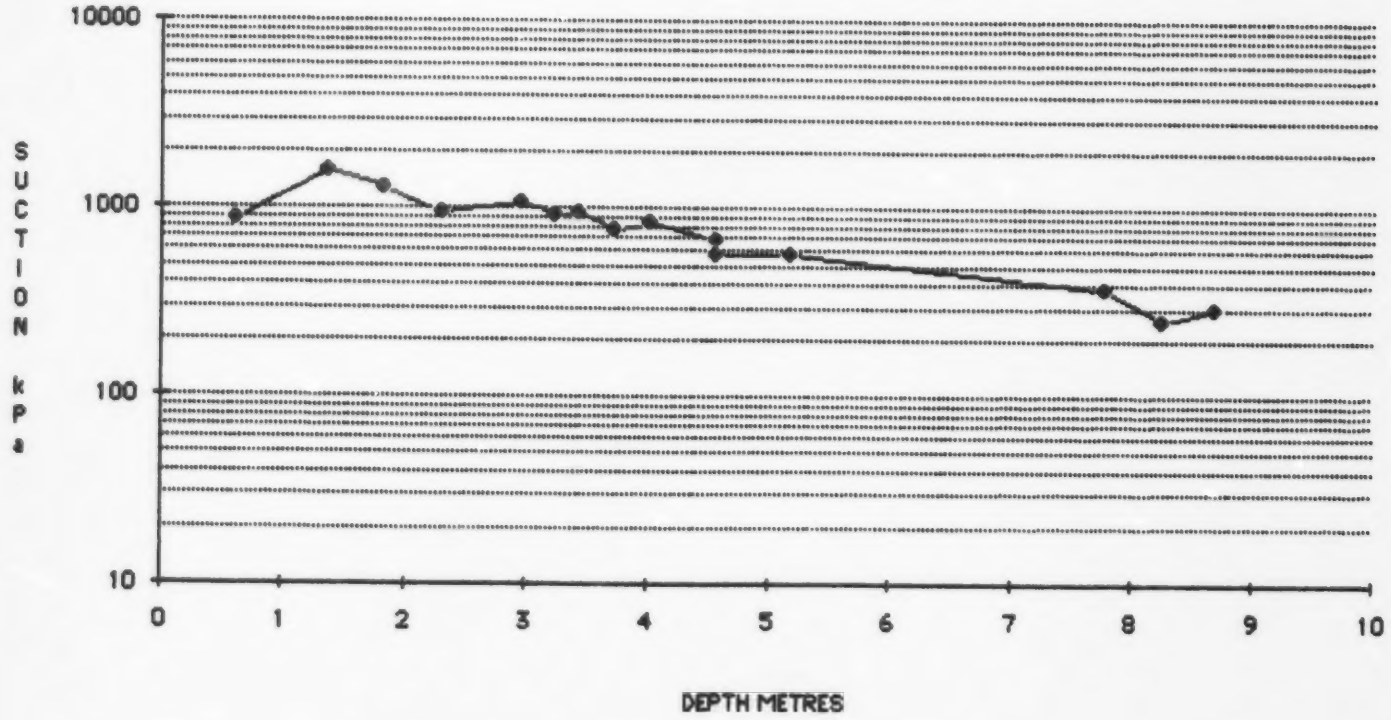


FIGURE 30 : PLOT OF TOTAL SUCTION VERSUS DEPTH FOR SITE #3
BY THE PSYCHROMETER METHOD

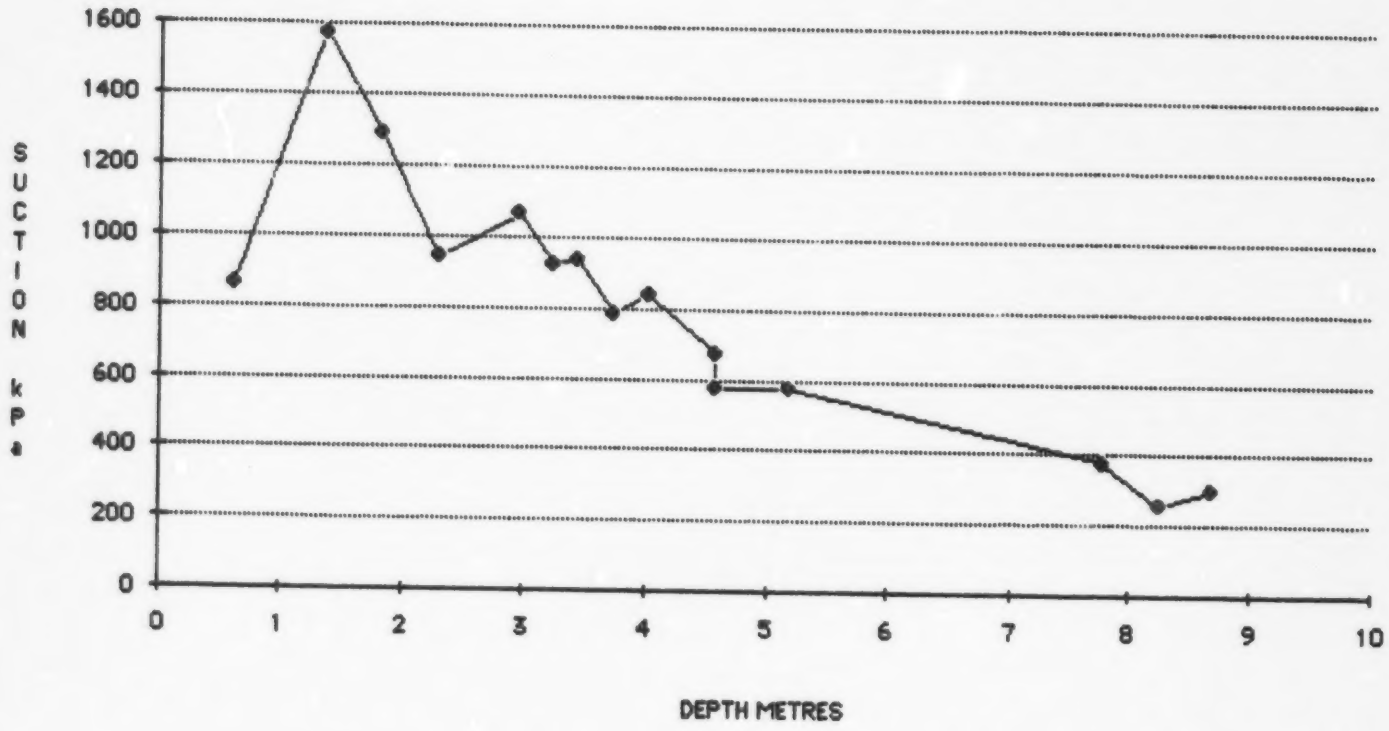
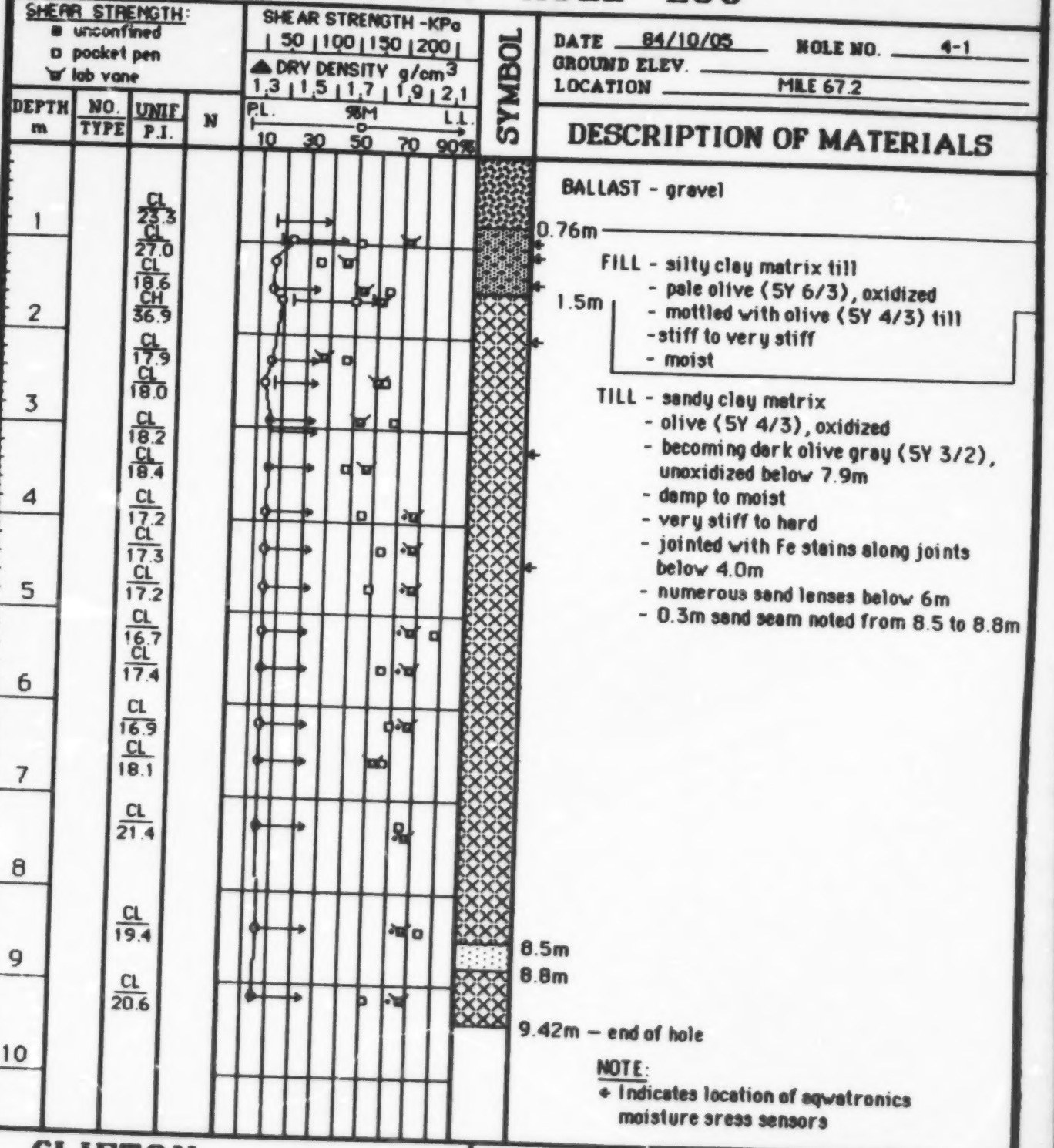


FIGURE 31 : PLOT OF TOTAL SUCTION VERSUS DEPTH FOR SITE #3
BY THE PSYCHROMETER METHOD

TEST HOLE LOG



DATE 84/10/05 HOLE NO. 4-1
GROUND ELEV.
LOCATION MILE 67.2

DESCRIPTION OF MATERIALS

BALLAST - gravel

0.76m

FILL - silty clay matrix till
- pale olive (5Y 6/3), oxidized
- mottled with olive (5Y 4/3) till
- stiff to very stiff
- moist

1.5m

TILL - sandy clay matrix
- olive (5Y 4/3), oxidized
- becoming dark olive gray (5Y 3/2), unoxidized below 7.9m
- damp to moist
- very stiff to hard
- jointed with Fe stains along joints below 4.0m
- numerous sand lenses below 6m
- 0.3m sand seam noted from 8.5 to 8.8m

8.5m

8.8m

9.42m – end of hole

NOTE:
+ Indicates location of aquatronics moisture sress sensors

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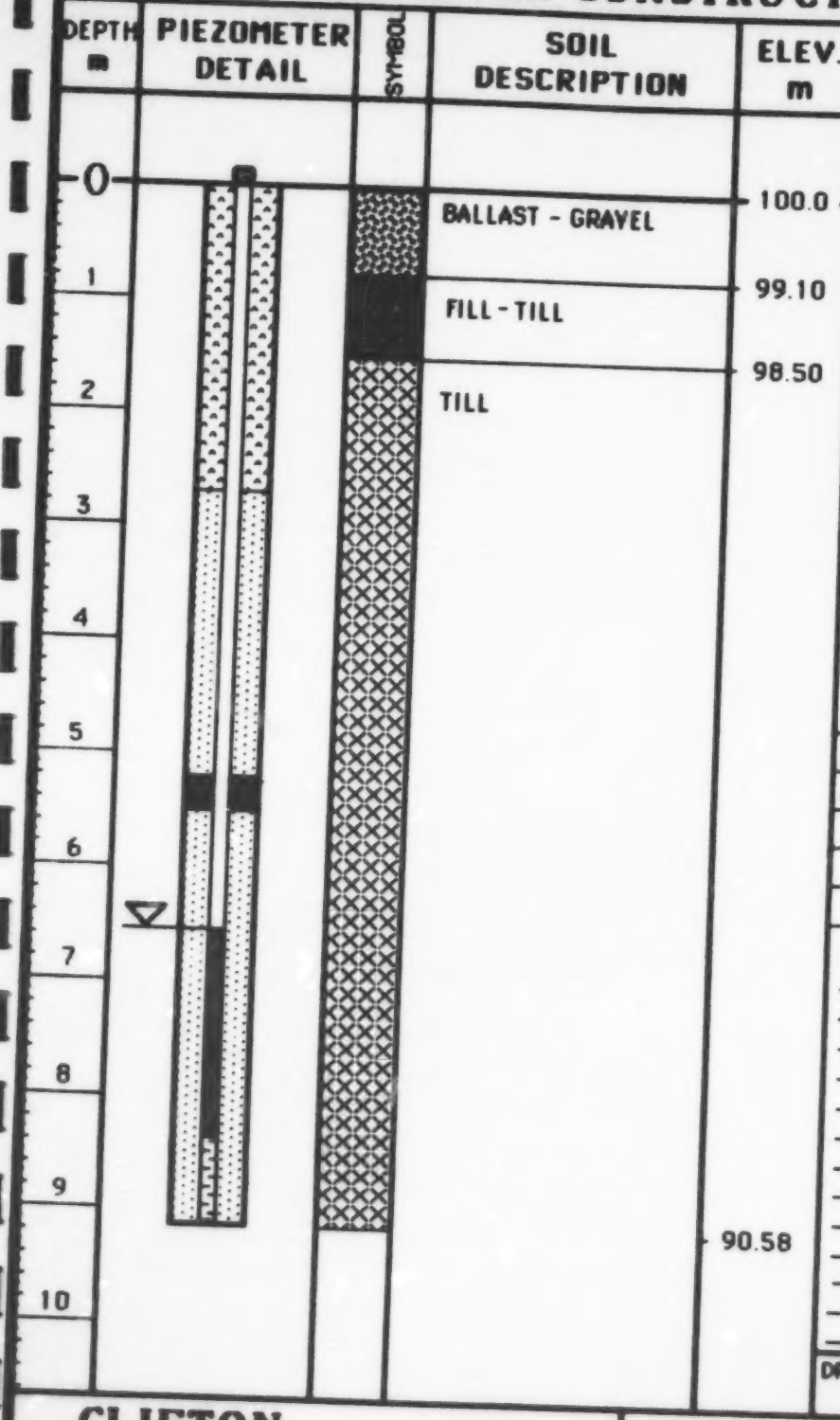
PROJECT ENGINEERING RESEARCH
LOCATION McLEAN, SASKATCHEWAN
PROJECT NO. R461 FIGURE NO. 32

PIEZOMETER CONSTRUCTION DETAILS



PIEZOMETER NO. 4-1
TEST HOLE NO. 4-1

LOCATION MILE 67.2 CP TRACKAGE
McLEAN
SASKATCHEWAN
TOP PIPE ELEV. 100.15m
GROUND ELEV. 100.0m
BASE SCREEN ELEV. 90.86m
TYPE OF PIPE 50mm Ø PVC
TYPE OF SCREEN 50 mm Ø RICE #10 SLOT
TEST HOLE DIA. 125 mm Ø
INST. DATE 84/10/05
TECHNICIAN PvdR /LTN
CONTRACTOR PROBE
DRILL BRATT 22

WATER LEVELS

DATE	TIME	DEPTH - m	ELEV. - m
/10/05	-	-	DRY
/12/07	-	4.70	95.8

REMARKS
All elevations referenced to top of tie
Top of tie elevation assumed 100.0m.

MATERIALS:
- CUTTINGS
- BENTONITE PELLETS
- WASHED CONCRETE SAND

DRAWN BY: PvdR
APPROVED BY: PvdR

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PROJECT ENGINEERING RESEARCH
LOCATION McLEAN, SASKATCHEWAN
PROJECT NO. R461 FIGURE NO. 33

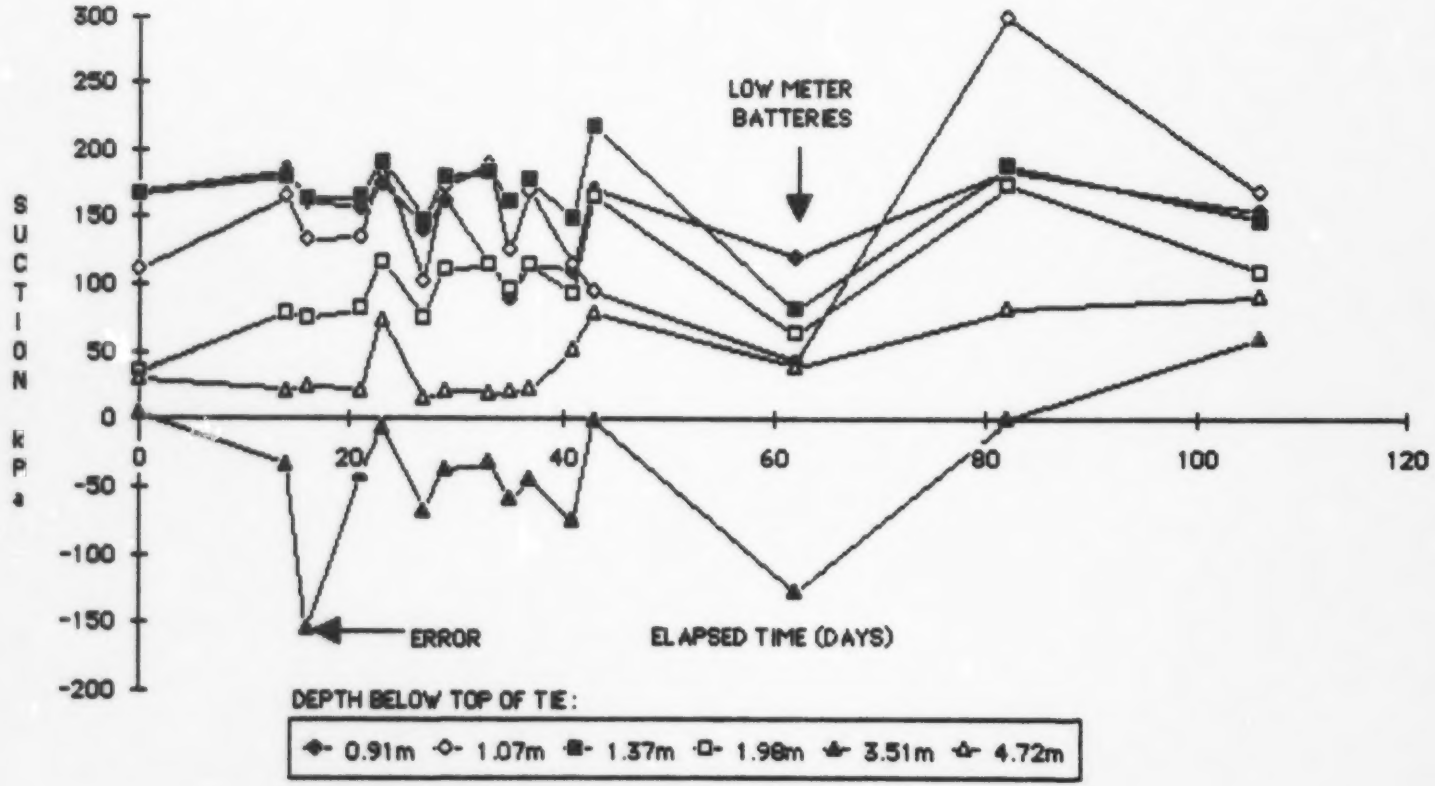

FIGURE 34 : PLOT OF SUCTION VERSUS ELAPSED TIME FOR AGWATRONICS MOISTURE STRESS SENSORS - SITE #4

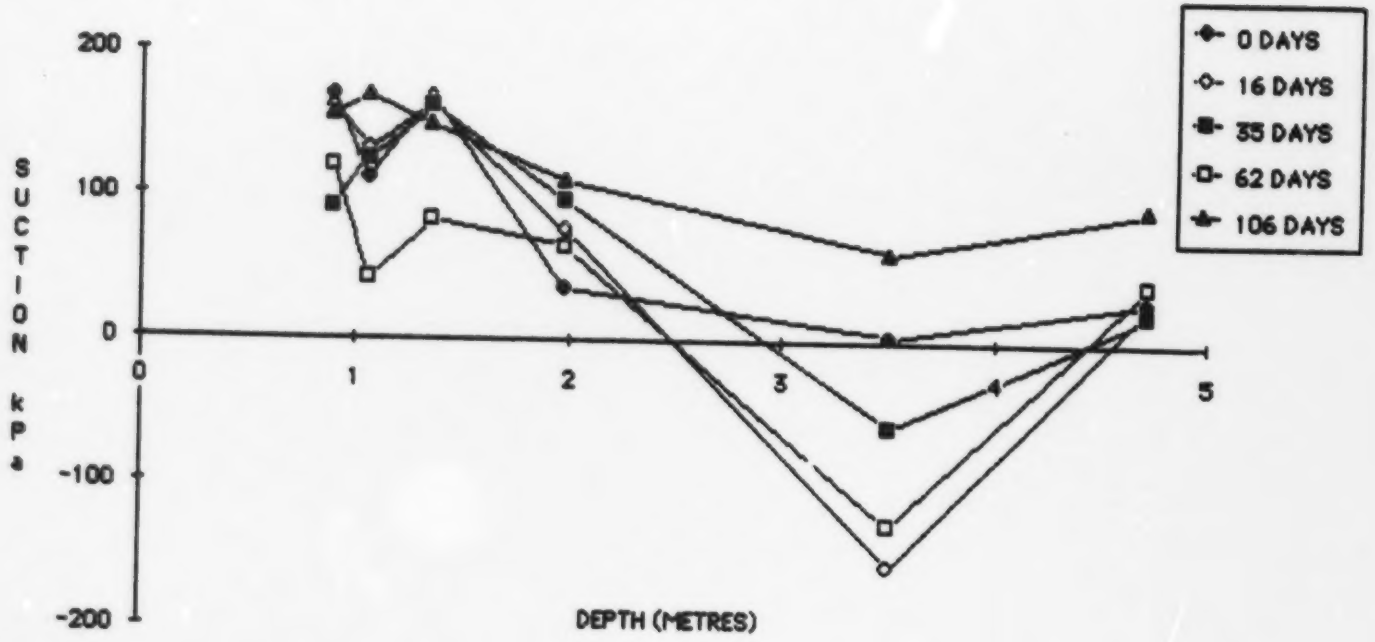

FIGURE 35 : PLOT OF MATRIC SUCTION VERSUS DEPTH AS DETERMINED BY AGWATRONICS MOISTURE STRESS SENSORS - SITE #4

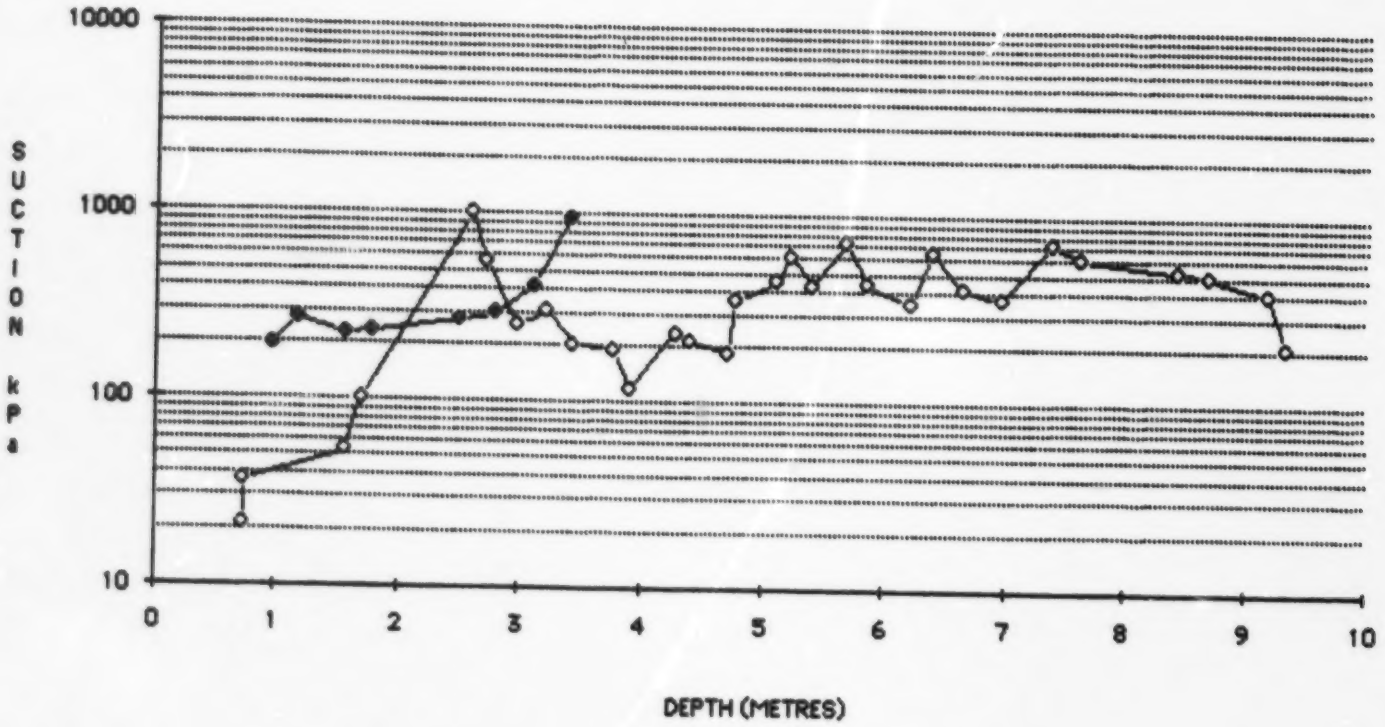

FIGURE 36 : MATRIC SUCTION VERSUS DEPTH FOR TEST HOLE 4-2
BY THE MCQUEEN AND MILLER FILTER PAPER METHOD

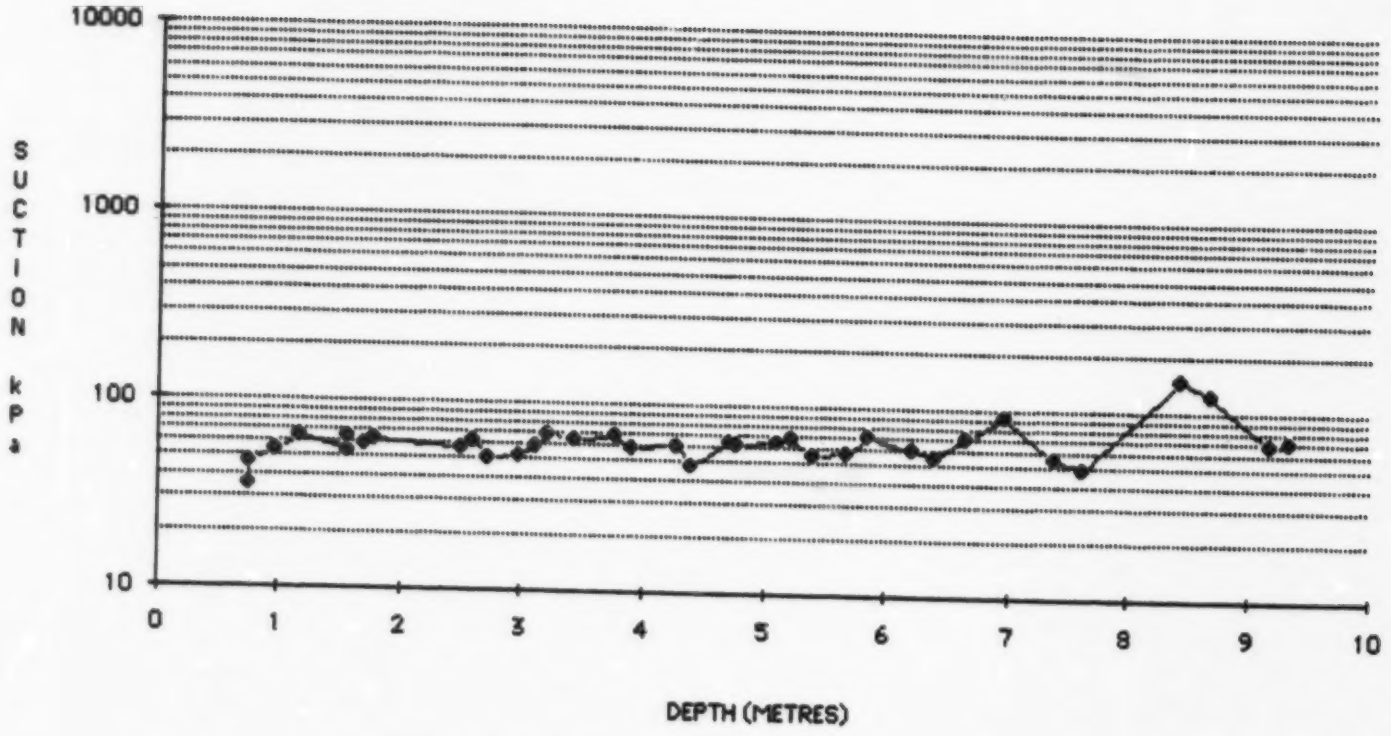

FIGURE 37 : MATRIC SUCTION VERSUS DEPTH FOR TEST HOLE 4-2
BY HAMBLIN'S FILTER PAPER METHOD

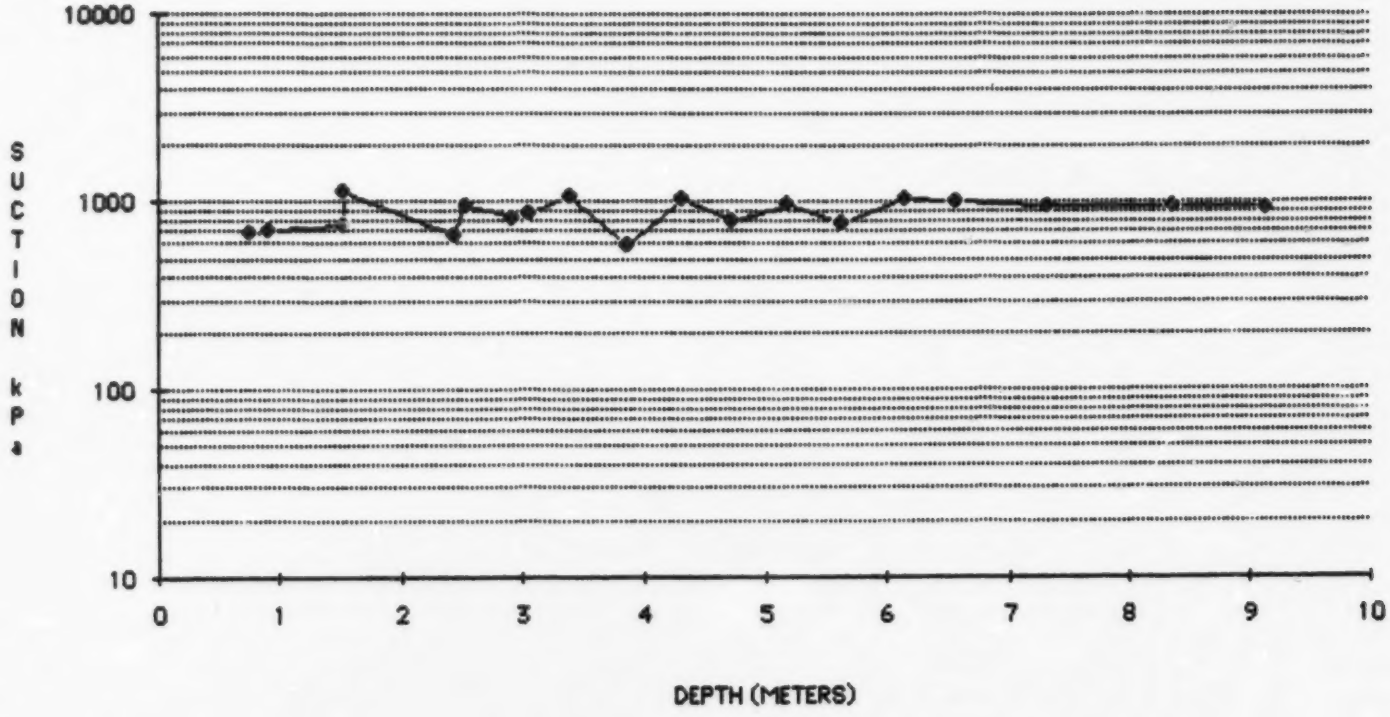

FIGURE 38 : TOTAL SUCTION VERSUS DEPTH FOR TEST HOLE 4-2 BY THE McQUEEN AND MILLER FILTER PAPER METHOD (NO CONTACT)

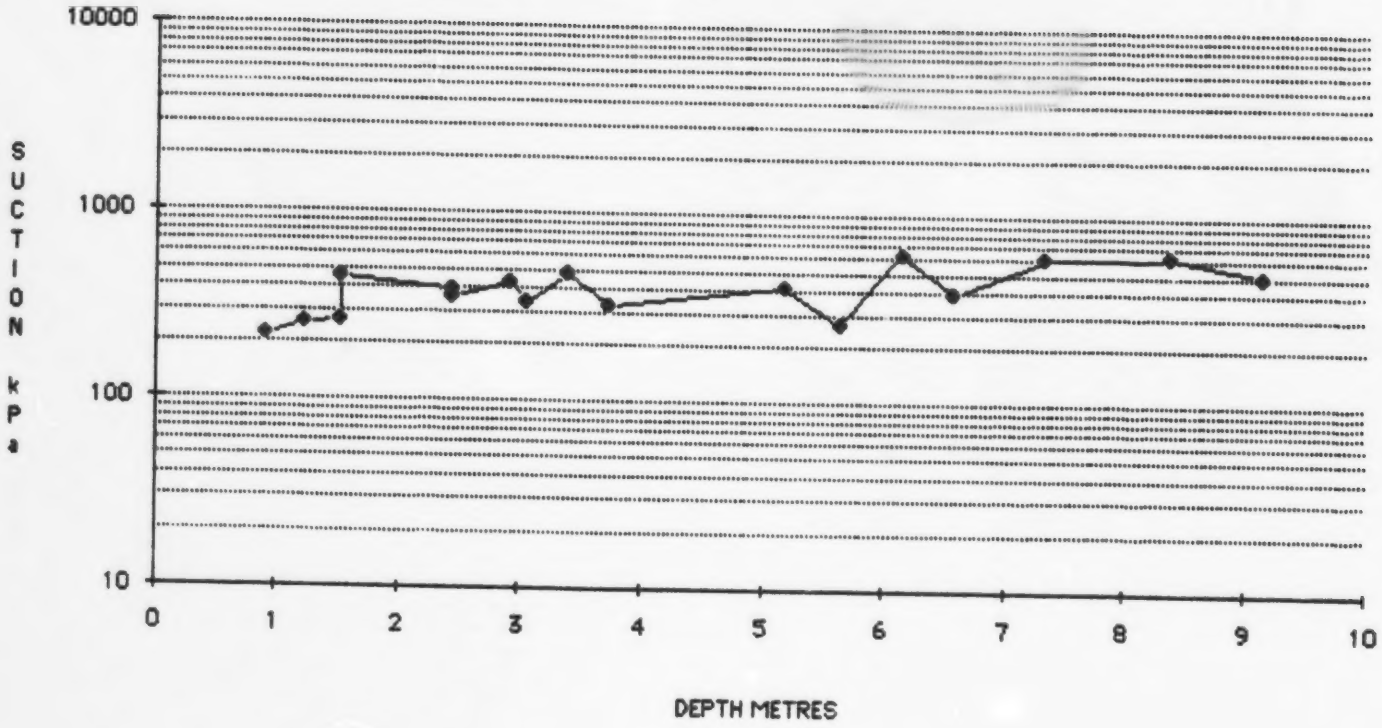

FIGURE 39 : PLOT OF TOTAL SUCTION VERSUS DEPTH FOR SITE #4
BY THE PSYCHROMETER METHOD

TEST HOLE LOG

SHEAR STRENGTH:
■ unconfined
□ pocket pen
lab vane

SHEAR STRENGTH -KPa
50 | 100 | 150 | 200
▲ DRY DENSITY g/cm³
1.3 | 1.5 | 1.7 | 1.9 | 2.1

DATE 84/10/30 HOLE NO. 5-1
GROUND ELEV.
LOCATION MILE 2.14 BEAMER SUBDIVISION

DEPTH m	NO. TYPE	UNIF P.I.	N	P.L. ○ W.M. L.L. (10 30 50 70 90%)	SYMBOL
1			7		
2		CH 27.1 / CL 27.9	9		
3		CL 27.6 / CL 18.7	13		
4		CL 24.5 / CH 30.5	13		
5		CH 35.8 / CH 28.0 / CH 31.2	9 / 10		
6		CH 34.7 / CL 17.4	23		
7		CH 38.9 / CH 43.1	12 / 7		
8			11		
9			16		
10					

DESCRIPTION OF MATERIALS

BALLAST - gravel and sand
- frozen to 0.5m

1.1m

FILL - clay, silty
- olive (5Y 4/3), oxidized
- stiff to very stiff
- moist
- laminated, stratified
- sandy below 2.6m
- becoming siltier below 3.8m
- rootlets, organic odour below 5.2m
- silty sand seam at 5.0m

5.8m TOPSOIL - organics, rubble
- silty clay matrix
- black (5Y 2/1)

6.1m

CLAY - silty
- dark grayish brown (2.5Y 4/2)
- oxidized, moist, stiff
- silt laminations throughout
- water bearing strata from 6.9 to 7.3m

7.9m SAND - fine to medium grained
- clayey, silty
- saturated, water bearing

8.8m end of hole

NOTE:
+ Indicates location of aqwatronics moisture sress sensors

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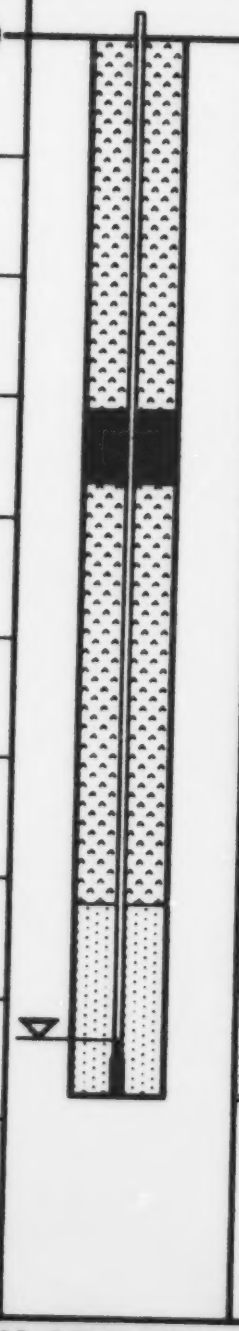
SASKATOON

PROJECT ENGINEERING RESEARCH
LOCATION FORT SASKATCHEWAN, ALBERTA
PROJECT NO. R461 FIGURE NO. 40

PIEZOMETER CONSTRUCTION DETAILS



SOIL DESCRIPTION	ELEV. m
	100.0
BALLAST	
	98.90
FILL - CLAY, SILTY	
	96.90
FILL - SILT, CLAYEY	
	94.20
TOPSOIL	
	93.90
CLAY, SILTY	
	92.10
SAND	
	91.20

PIEZOMETER NO. 5-1
TEST HOLE NO. 5-1

LOCATION MILE 2.14 BEAMER SUBDIV
FORT SASKATCHEWAN
ALBERTA
TOP PIPE ELEV. 100.27m
GROUND ELEV. 100.0m
BASE SCREEN ELEV. 91.2m
TYPE OF PIPE 25mm Ø PVC
TYPE OF SCREEN 25mm Ø
CASAGRANDE TIP
TEST HOLE DIA. 150 mm Ø
INST. DATE 84/10/30
TECHNICIAN PvdR
CONTRACTOR MOBILE AUGERS
DRILL MOBILE B60

WATER LEVELS

DATE	TIME	DEPTH - m	ELEV. - m
/10/30	-	8.57	93.60
/12/06	-	6.34	91.70

REMARKS
All elevations referenced to top of tie.
Top of tie elevation assumed 100.0m.

MATERIALS:
- CUTTINGS
- BENTONITE PELLETS
- SAND (SIL-9)

DRAWN BY: PvdR
APPROVED BY: PvdR

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REGINA
SASKATOON

PROJECT ENGINEERING RESEARCH
LOCATION FORT SASKATCHEWAN, ALBERTA
PROJECT NO. R461 FIGURE NO. 41

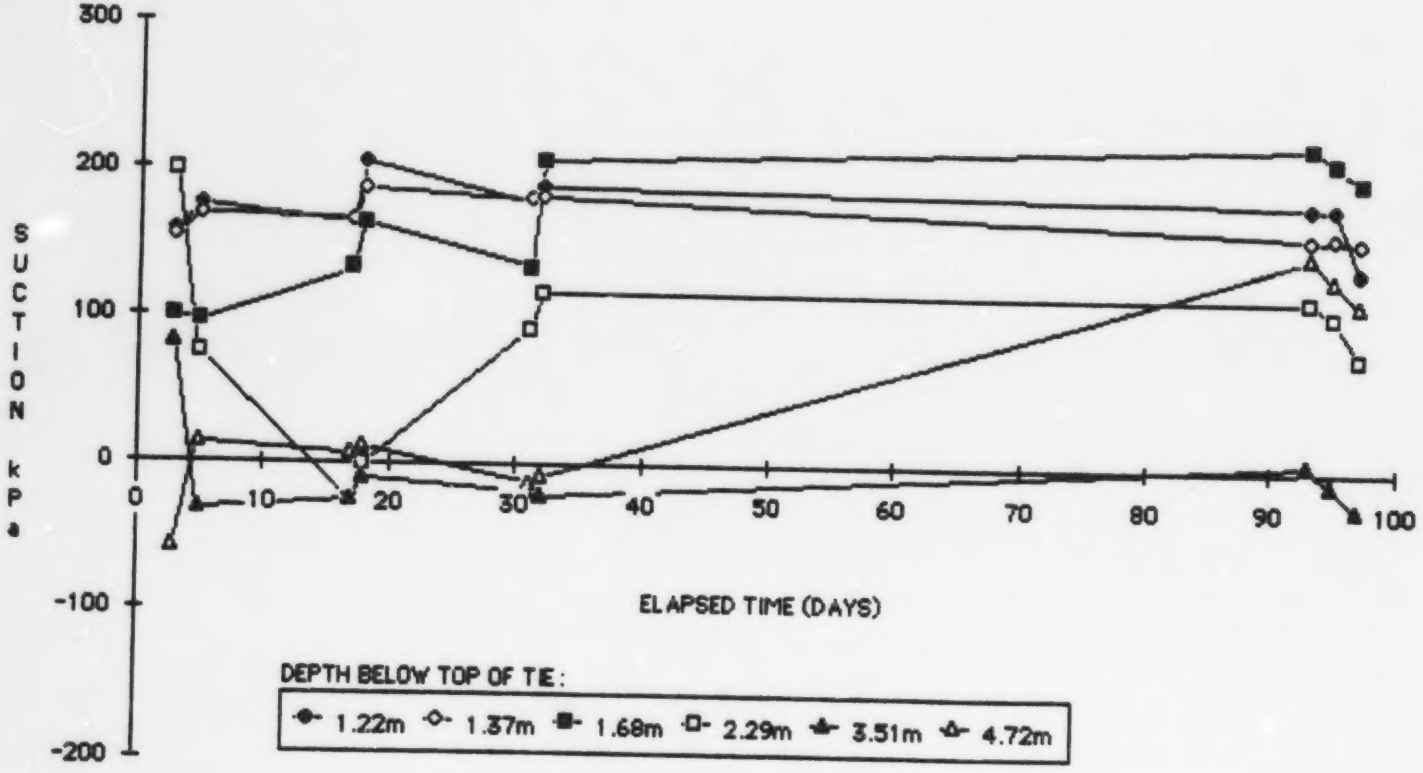

FIGURE 42 : PLOT OF SUCTION VERSUS ELAPSED TIME FOR AGWATRONICS MOISTURE STRESS SENSORS - SITE #5

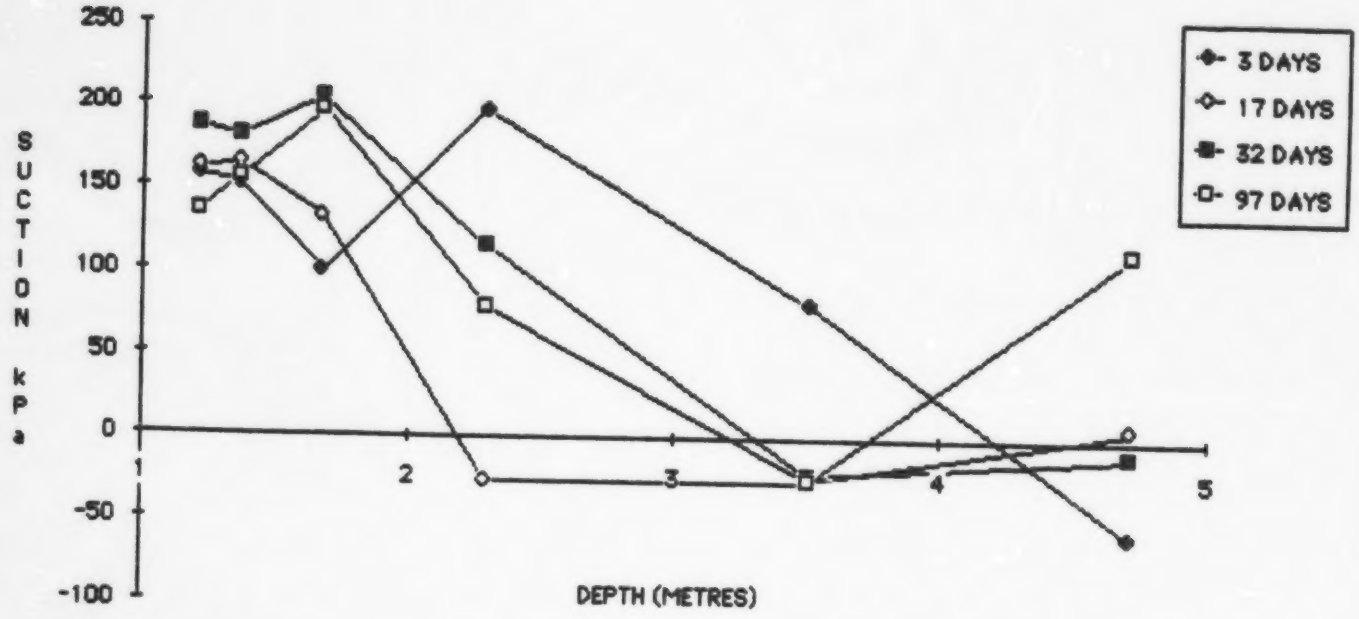

FIGURE 43 : PLOT OF MATRIC SUCTION VERSUS DEPTH AS DETERMINED BY AGWATRONICS MOISTURE STRESS SENSORS - SITE #5

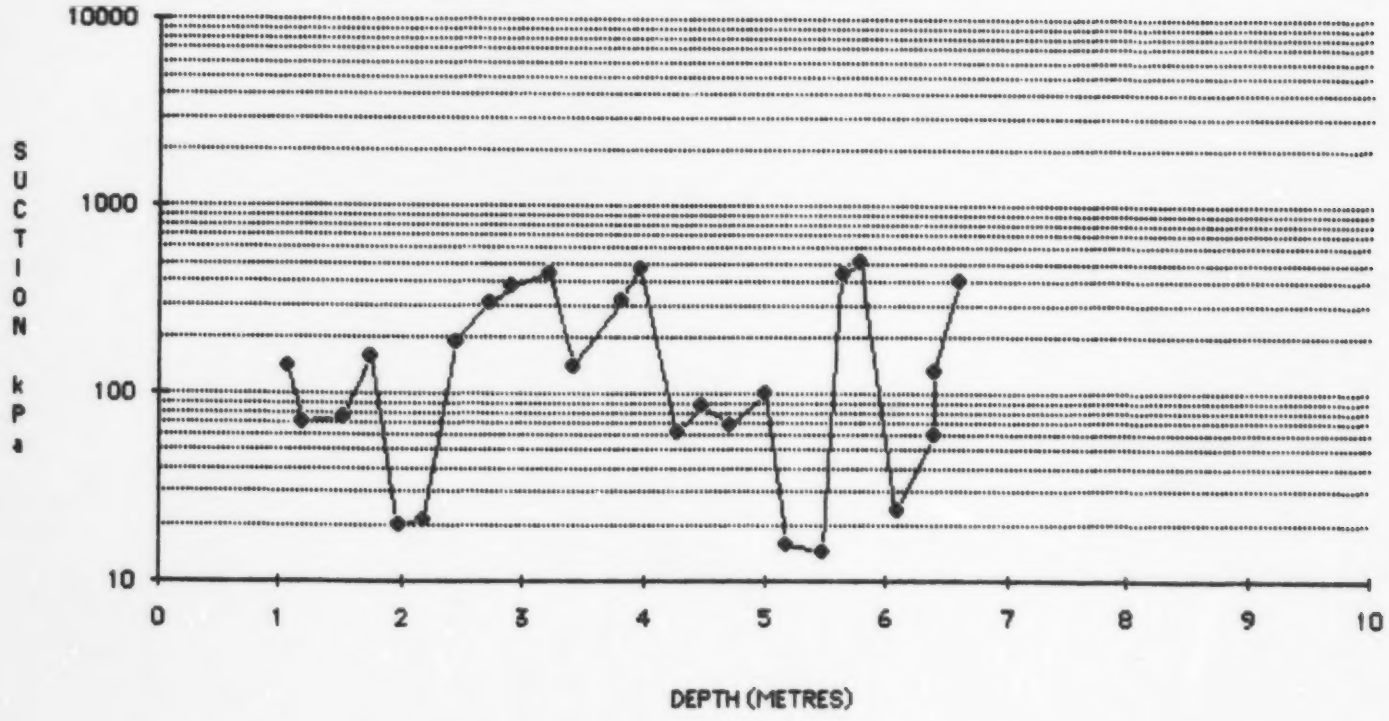

FIGURE 44 : MATRIC SUCTION VERSUS DEPTH FOR TEST HOLE 5-2 BY THE McQUEEN AND MILLER FILTER PAPER METHOD

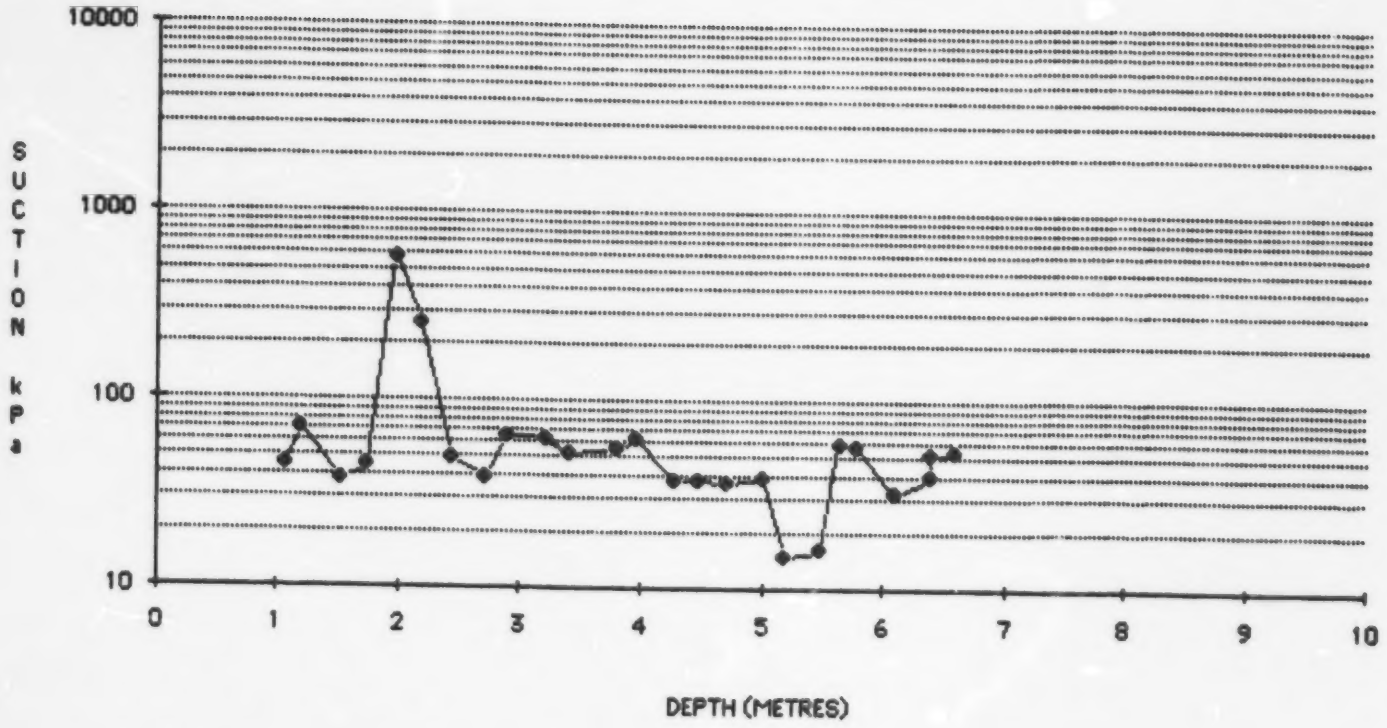

FIGURE 45 : MATRIC SUCTION VERSUS DEPTH FOR TEST HOLE 5-2
BY HAMBLIN'S FILTER PAPER METHOD

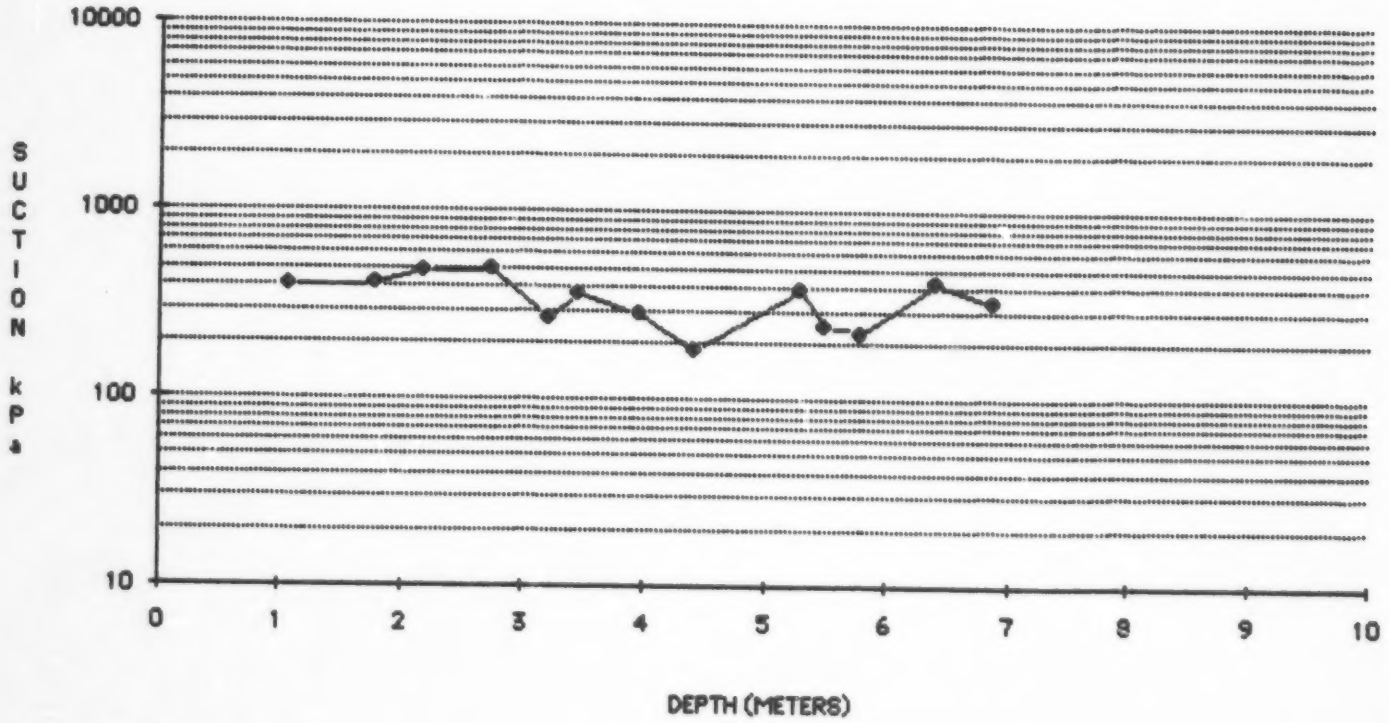

FIGURE 46 : TOTAL SUCTION VERSUS DEPTH FOR TEST HOLE 5-2 AFTER THE MoQUEEN AND MILLER FILTER PAPER METHOD (NO CONTACT)

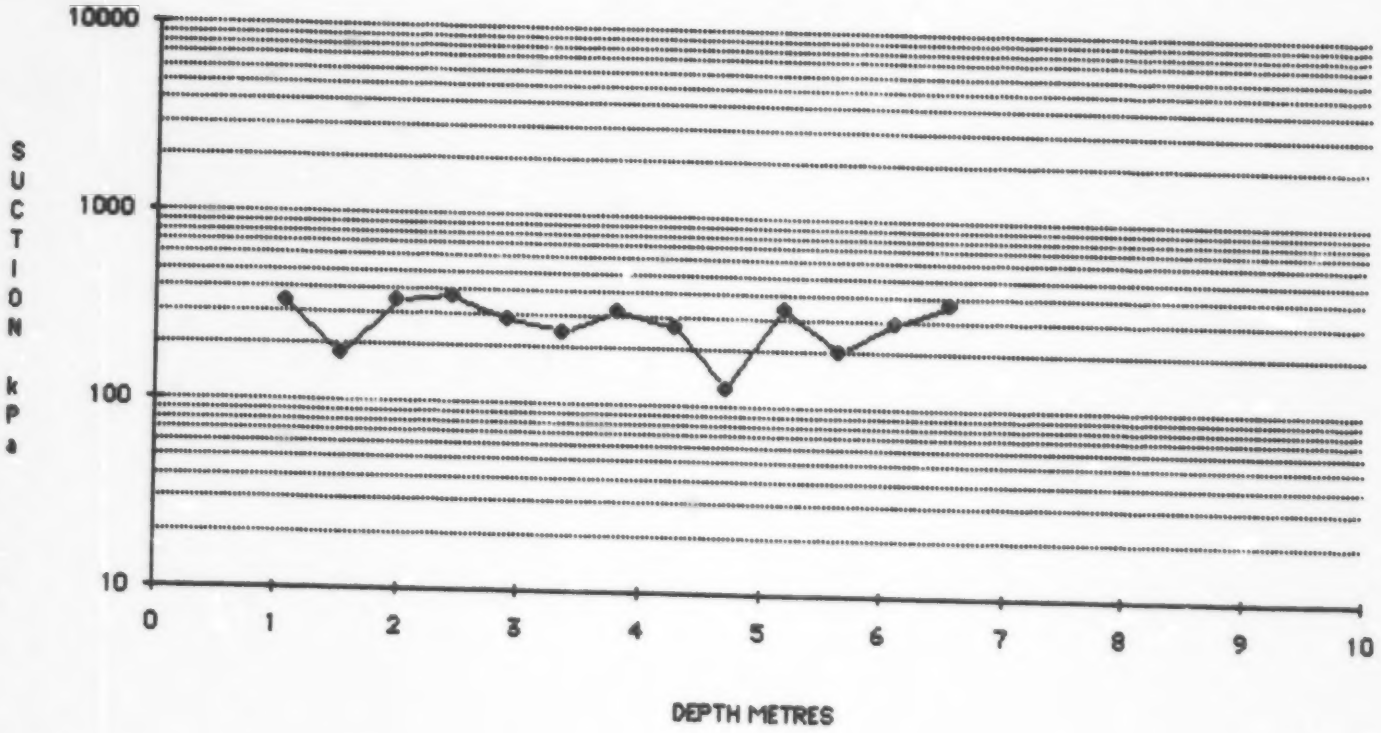

FIGURE 47 : PLOT OF TOTAL SUCTION VERSUS DEPTH FOR SITE #5
BY THE PSYCHROMETER METHOD

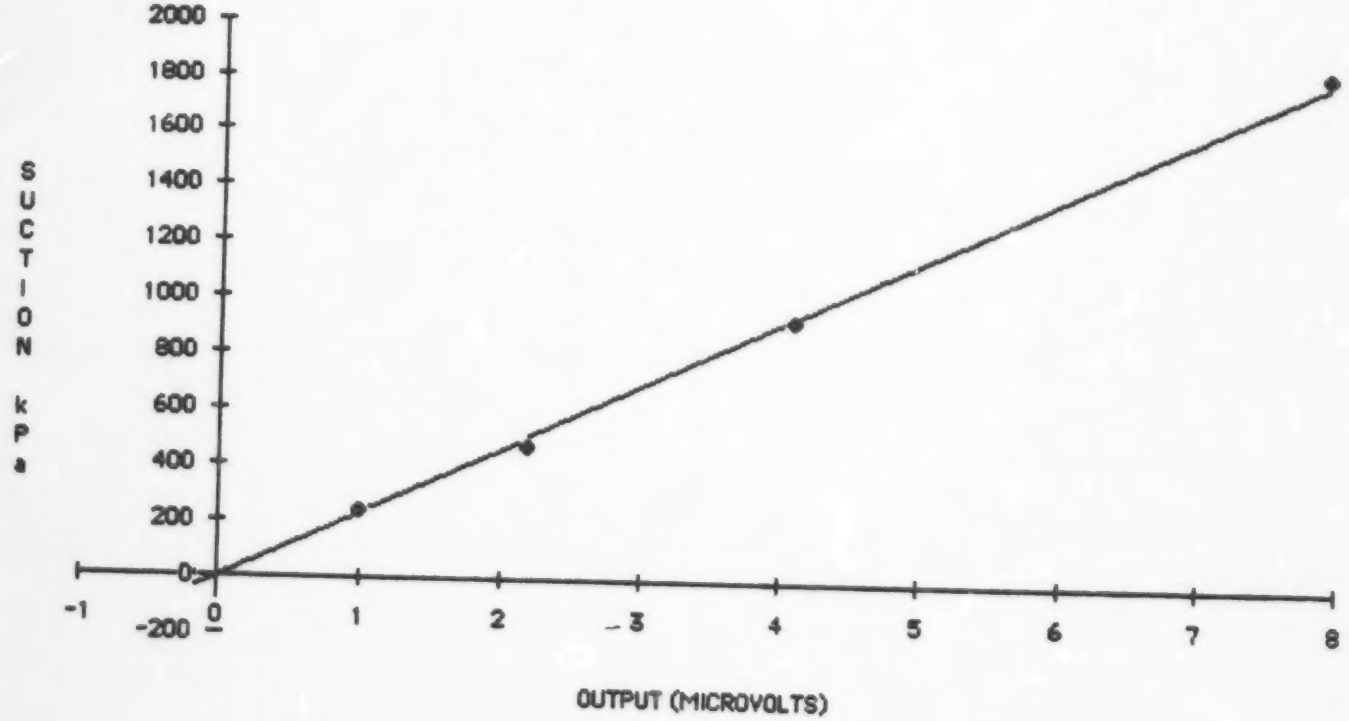

FIGURE 48 : PLOT OF SUCTION VERSUS PSYCHROMETER OUTPUT
FOR J.R.D. MERRILL PSYCHROMETER #1

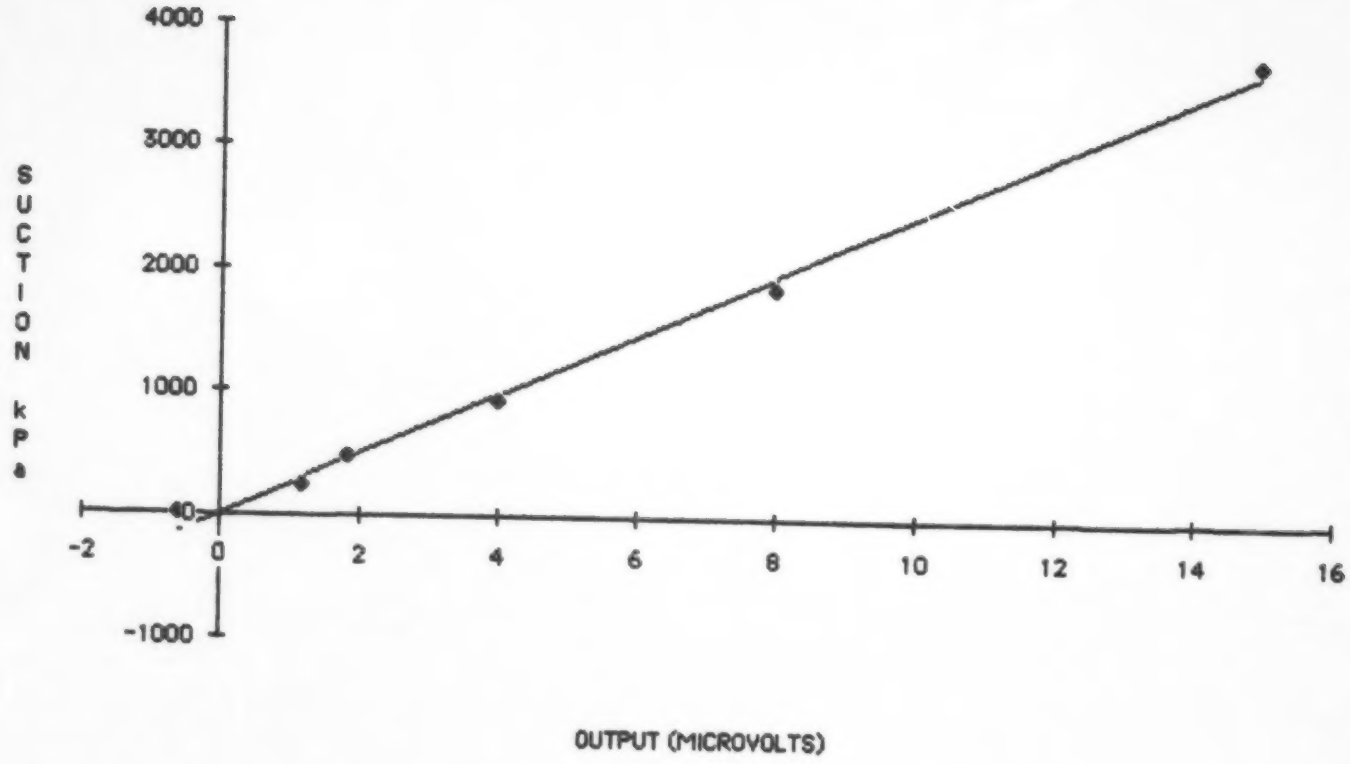

FIGURE 49: PLOT OF SUCTION VERSUS PSYCHROMETER OUTPUT FOR J.R.D. MERRILL PSYCHROMETER #2

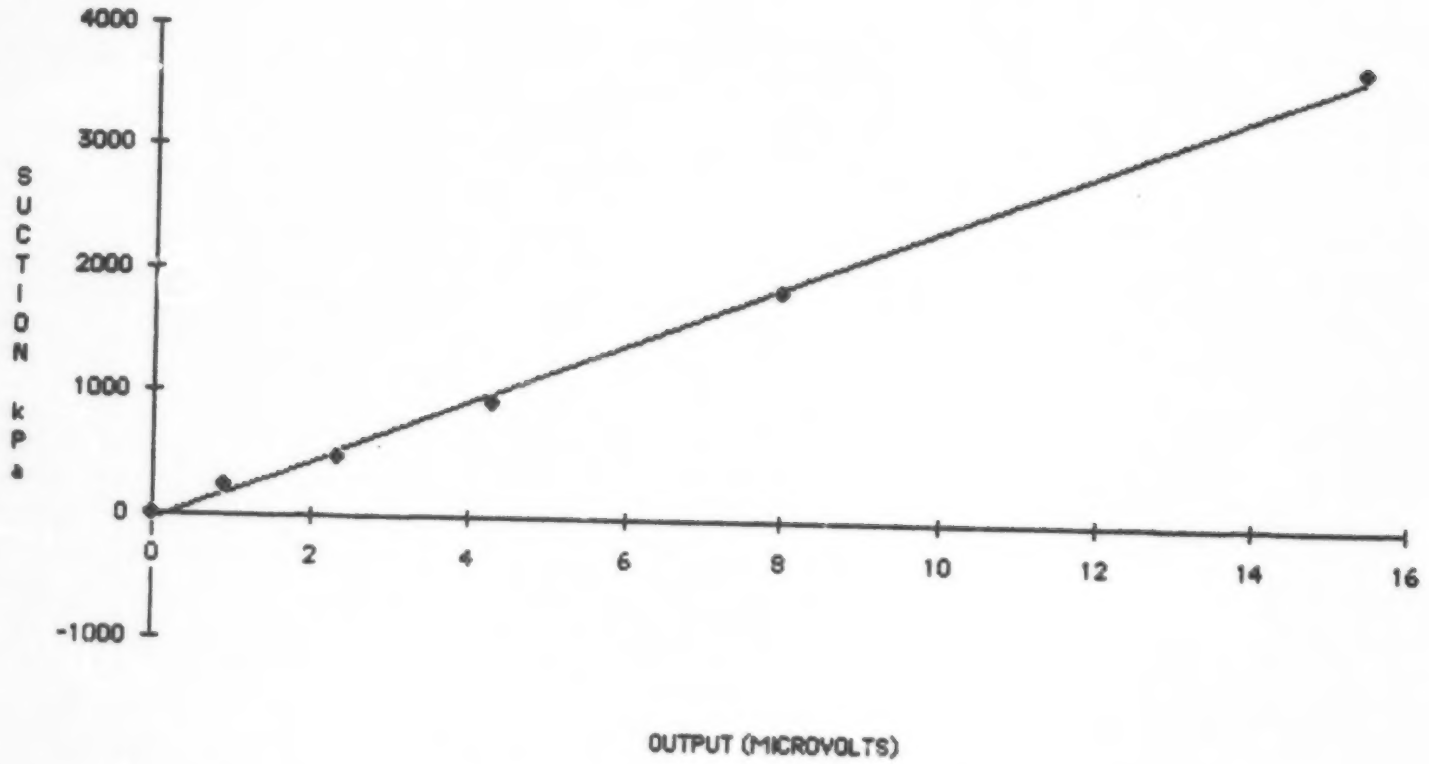

FIGURE 50 : PLOT OF SUCTION VERSUS PSYCHROMETER OUTPUT FOR J.R.D. MERRILL PSYCHROMETER #3

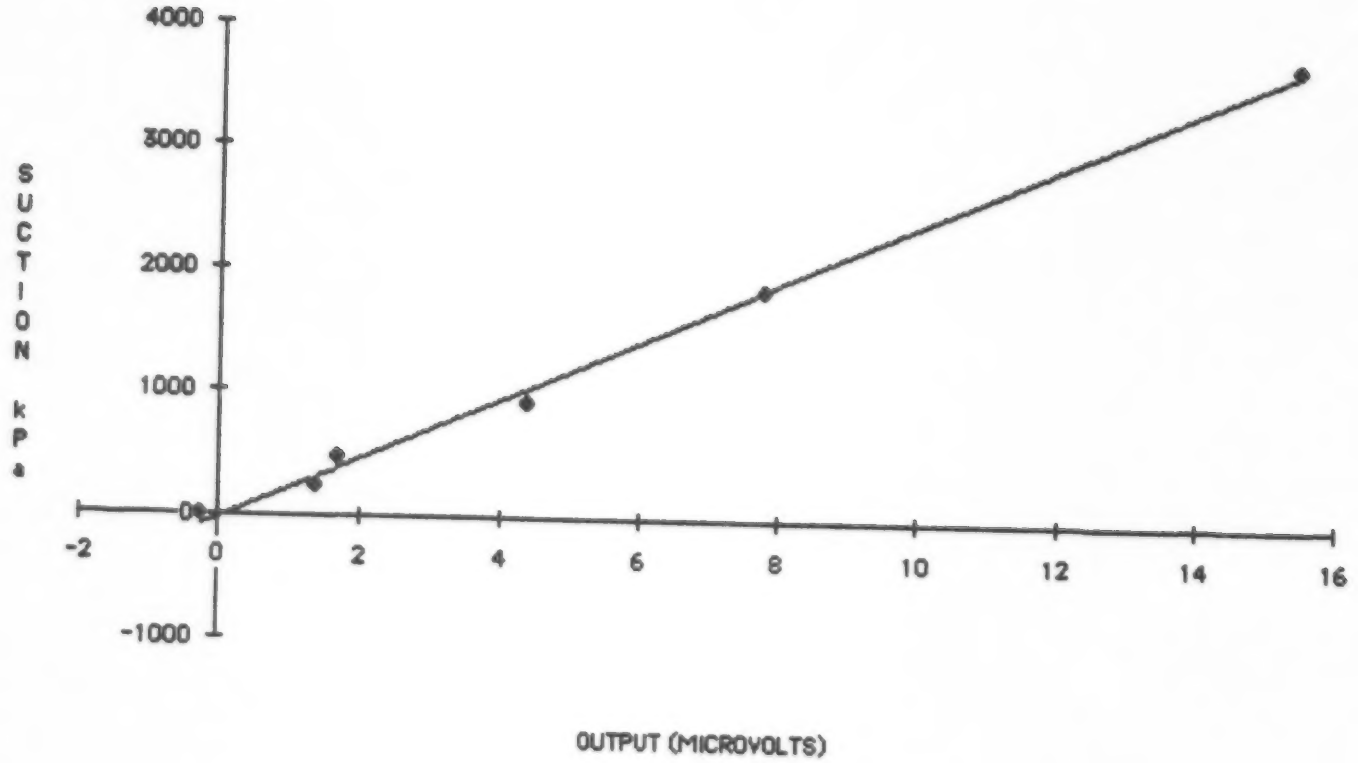

FIGURE 51 : PLOT OF SUCTION VERSUS PSYCHROMETER OUTPUT FOR J.R.D. MERRILL PSYCHROMETER #4

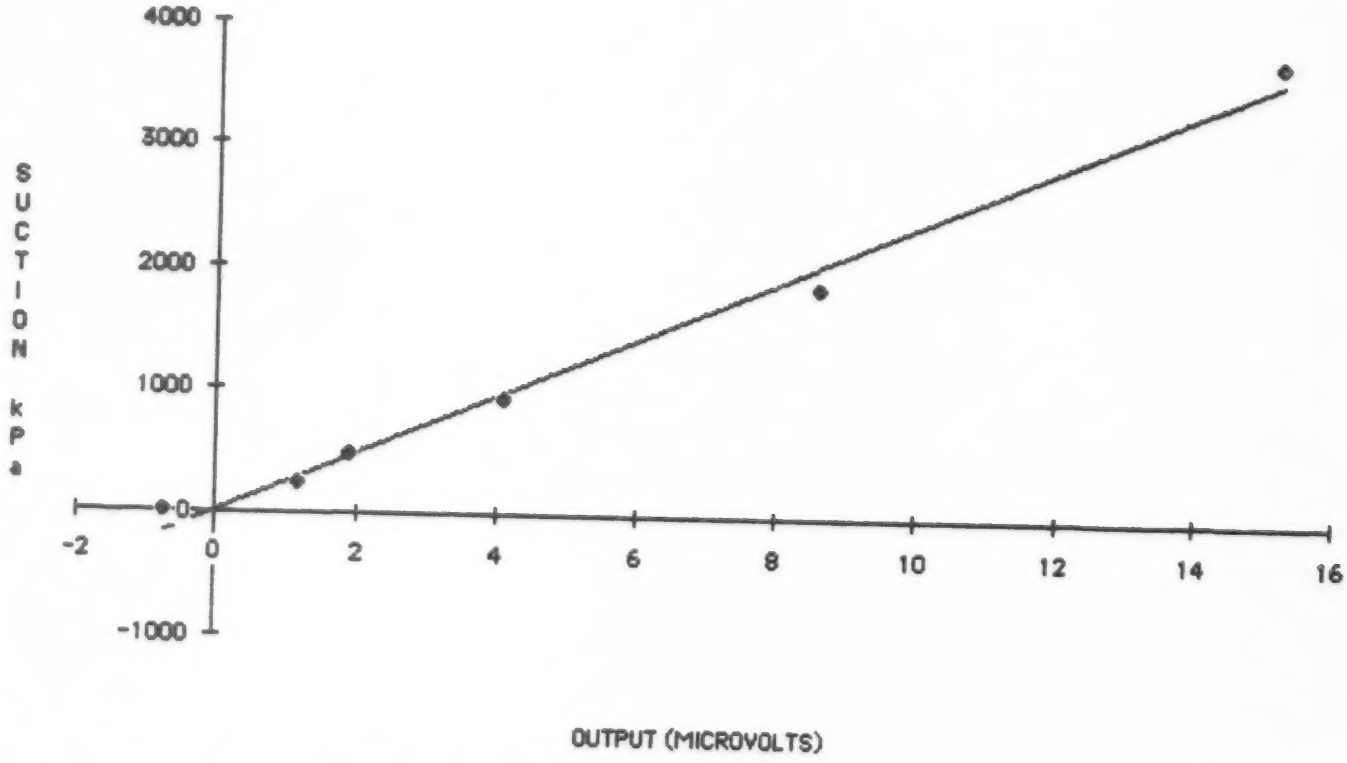

FIGURE 52 : PLOT OF SUCTION VERSUS PSYCHROMETER OUTPUT FOR J.R.D. MERRILL PSYCHROMETER #5

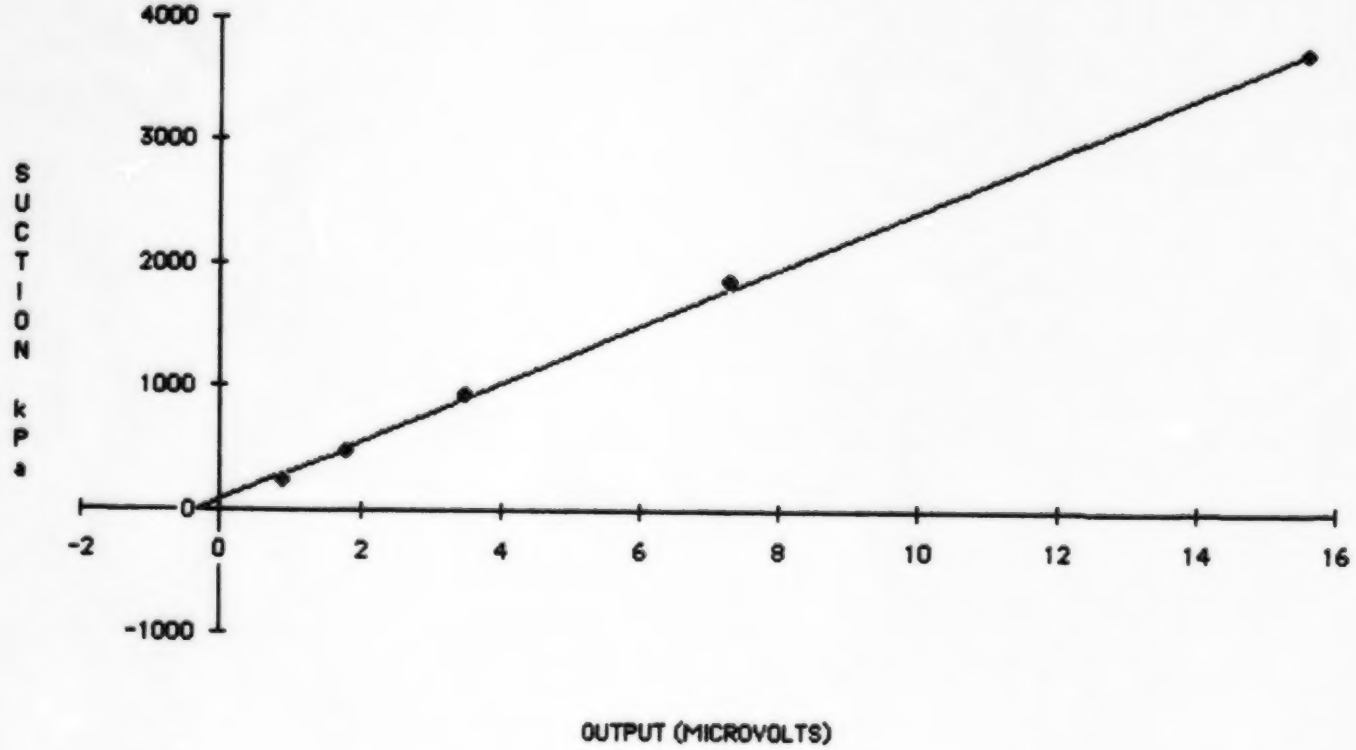

FIGURE 53 : PLOT OF SUCTION VERSUS PSYCHROMETER OUTPUT FOR J.R.D. MERRILL PSYCHROMETER #6

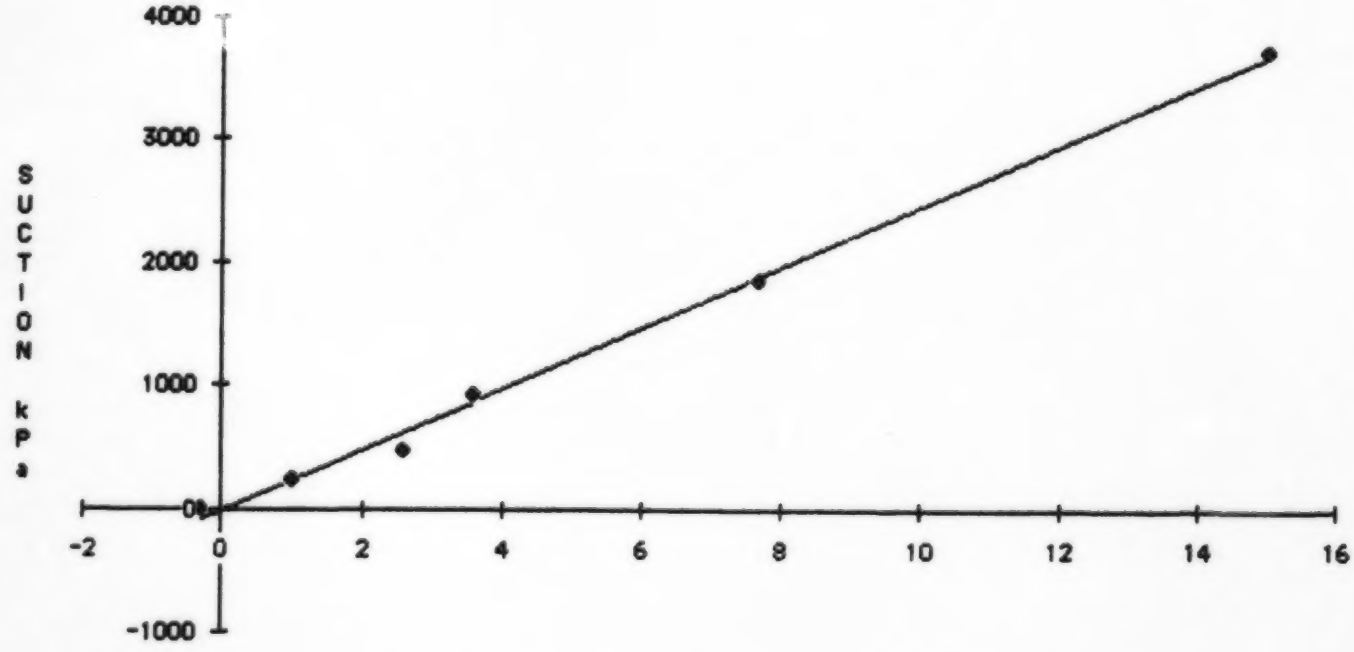

FIGURE 54 : PLOT OF SUCTION VERSUS PSYCHROMETER OUTPUT FOR J.R.D. MERRILL PSYCHROMETER #7

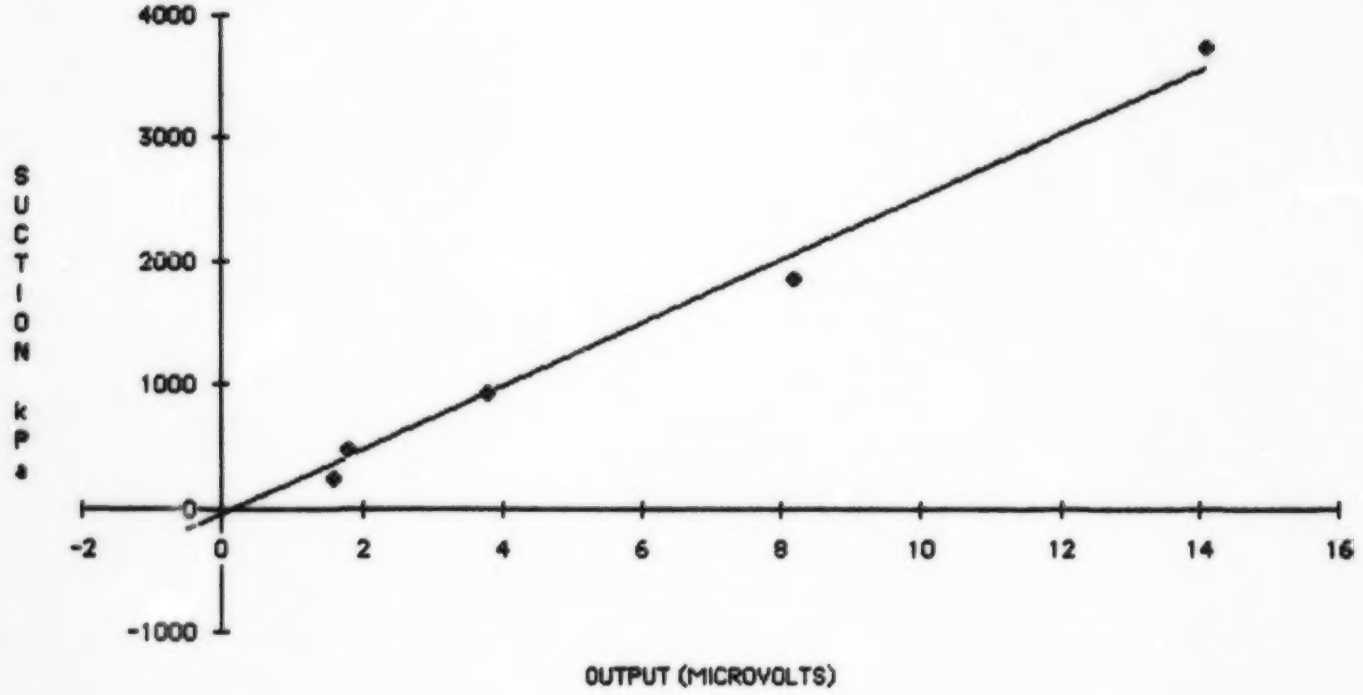

FIGURE 55 : PLOT OF SUCTION VERSUS PSYCHROMETER OUTPUT FOR J.R.D. MERRILL PSYCHROMETER #8

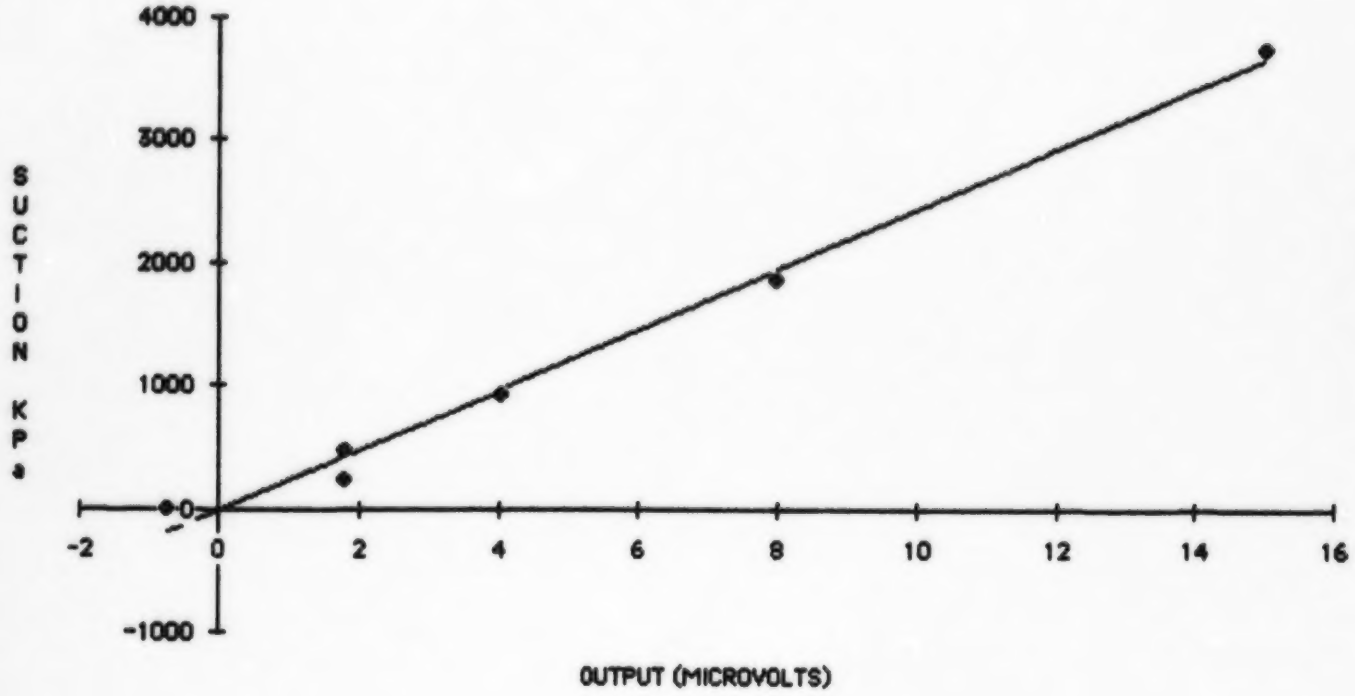

FIGURE 56 : PLOT OF SUCTION VERSUS PSYCHROMETER OUTPUT FOR J.R.D. MERRILL PSYCHROMETER #9

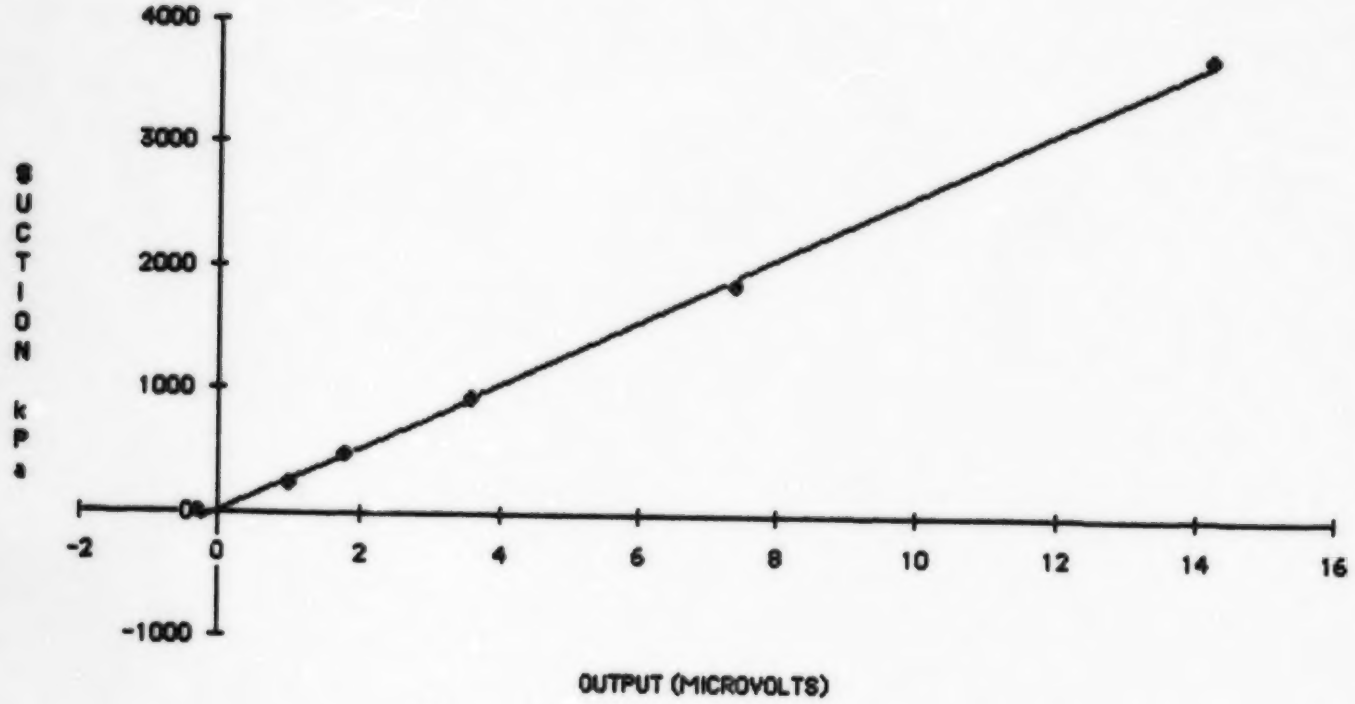

FIGURE 57 : PLOT OF SUCTION VERSUS PSYCHROMETER OUTPUT FOR J.R.D. MERRILL PSYCHROMETER #10

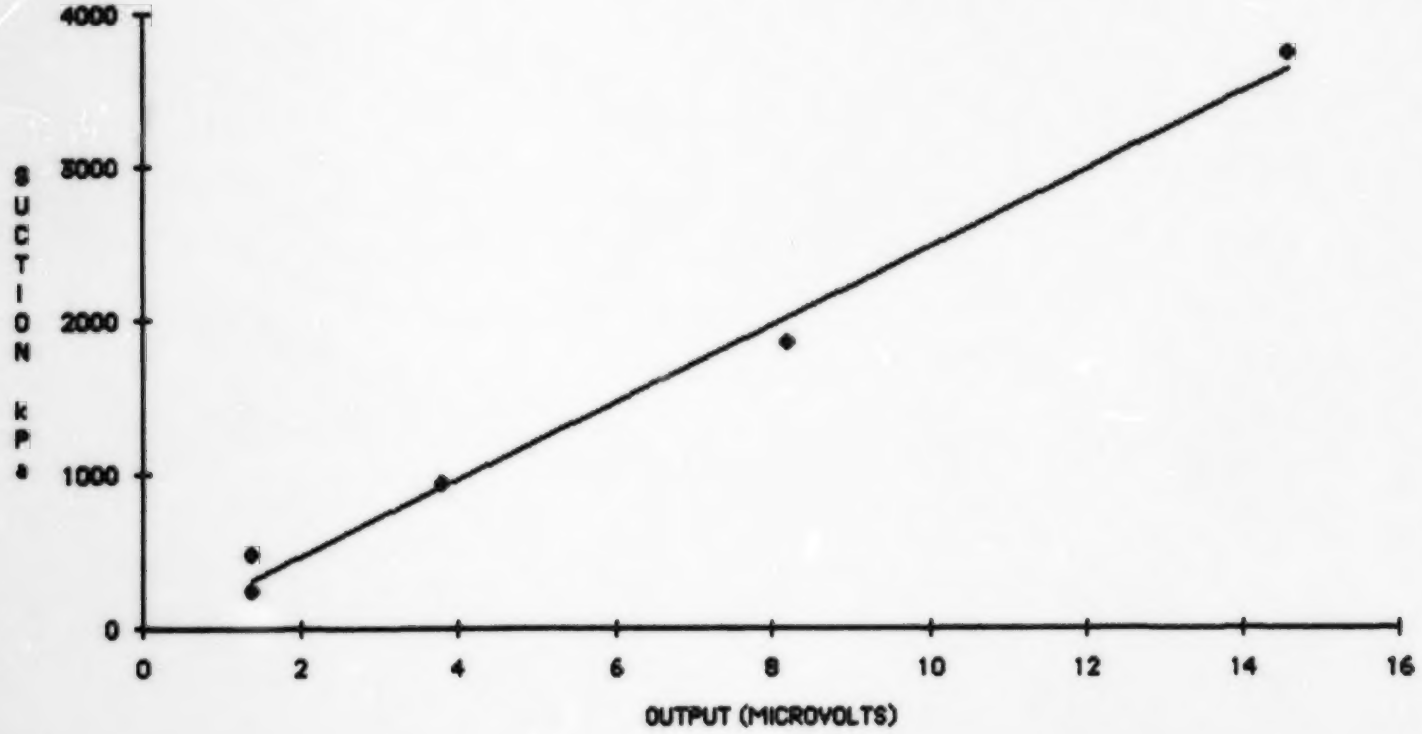

FIGURE 58 : PLOT OF SUCTION VERSUS PSYCHROMETER OUTPUT FOR J.R.D. MERRILL PSYCHROMETER #11

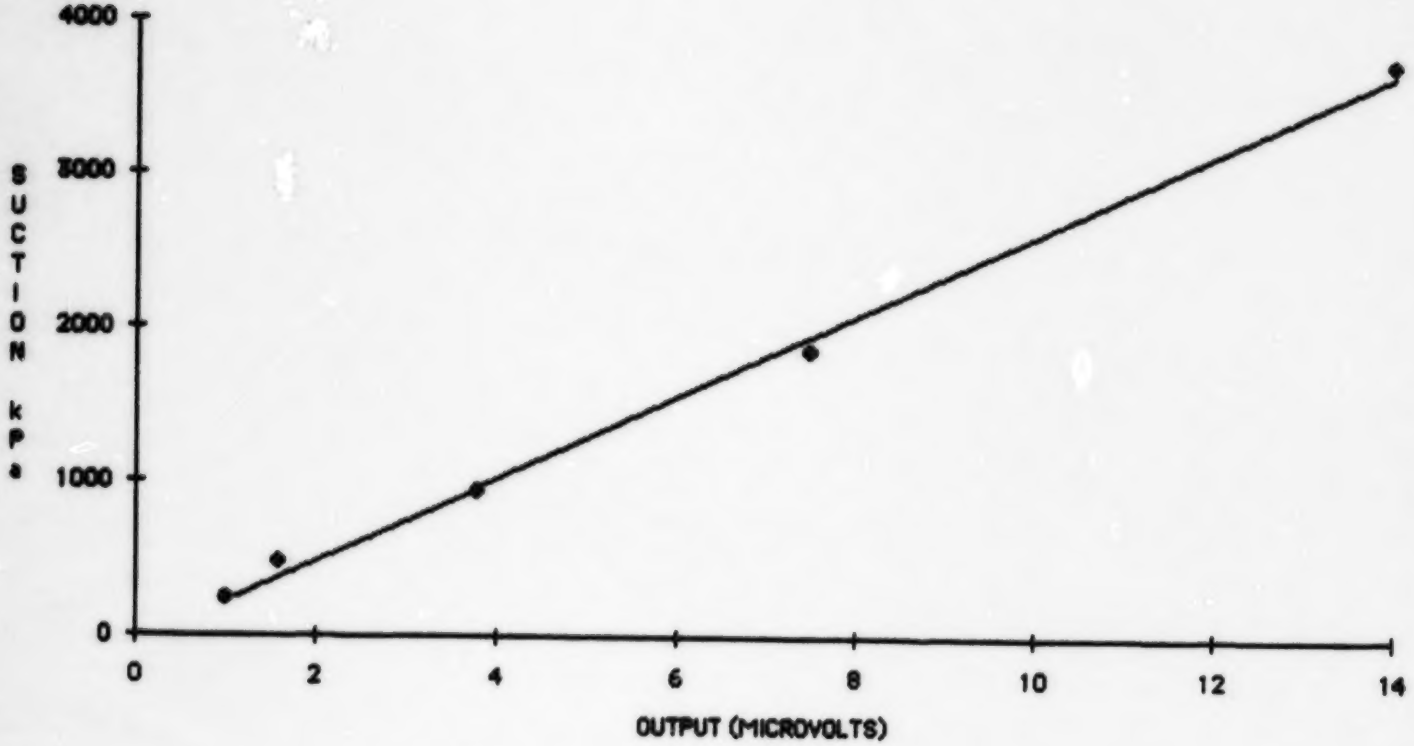

FIGURE 59 : PLOT OF SUCTION VERSUS PSYCHROMETER OUTPUT FOR J.R.D. MERRILL PSYCHROMETER #12

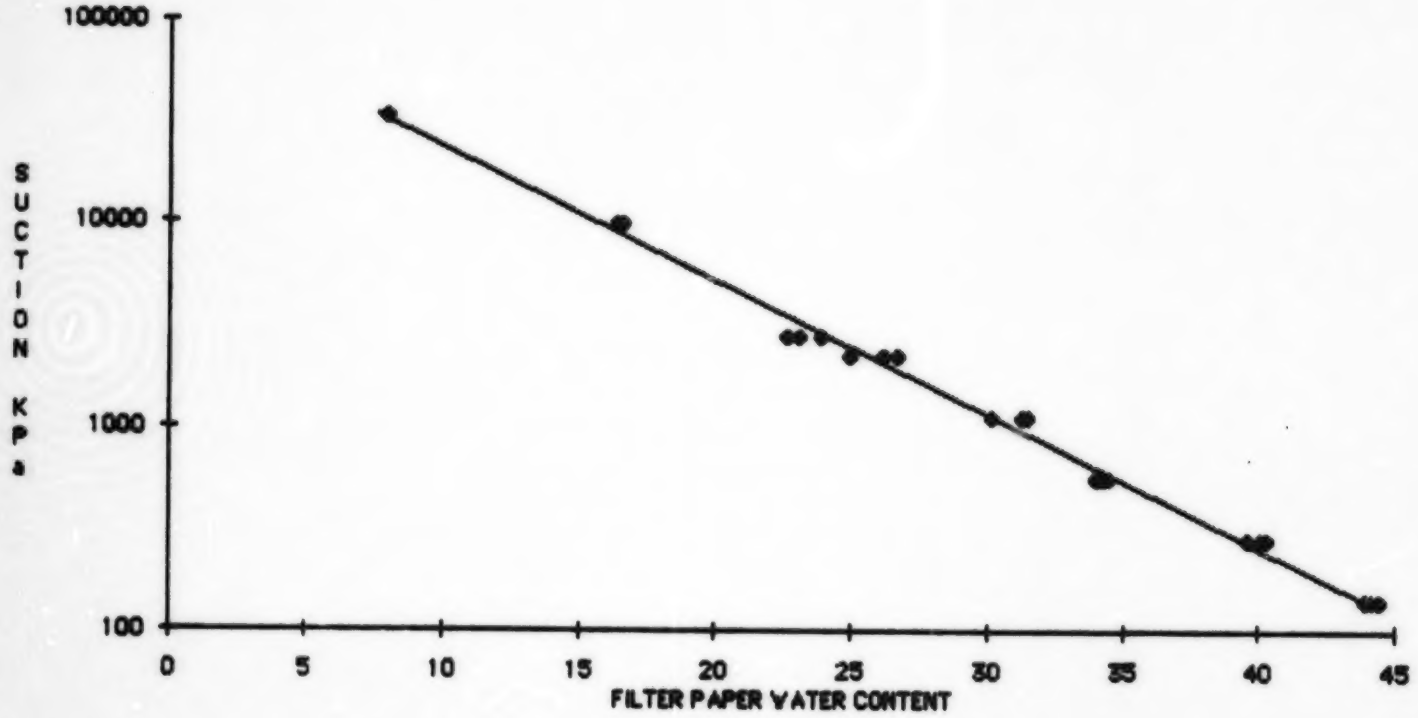

FIGURE 60 : WATER CONTENT OF FILTER PAPER VERSUS SUCTION
AFTER MILLER AND BRANSON

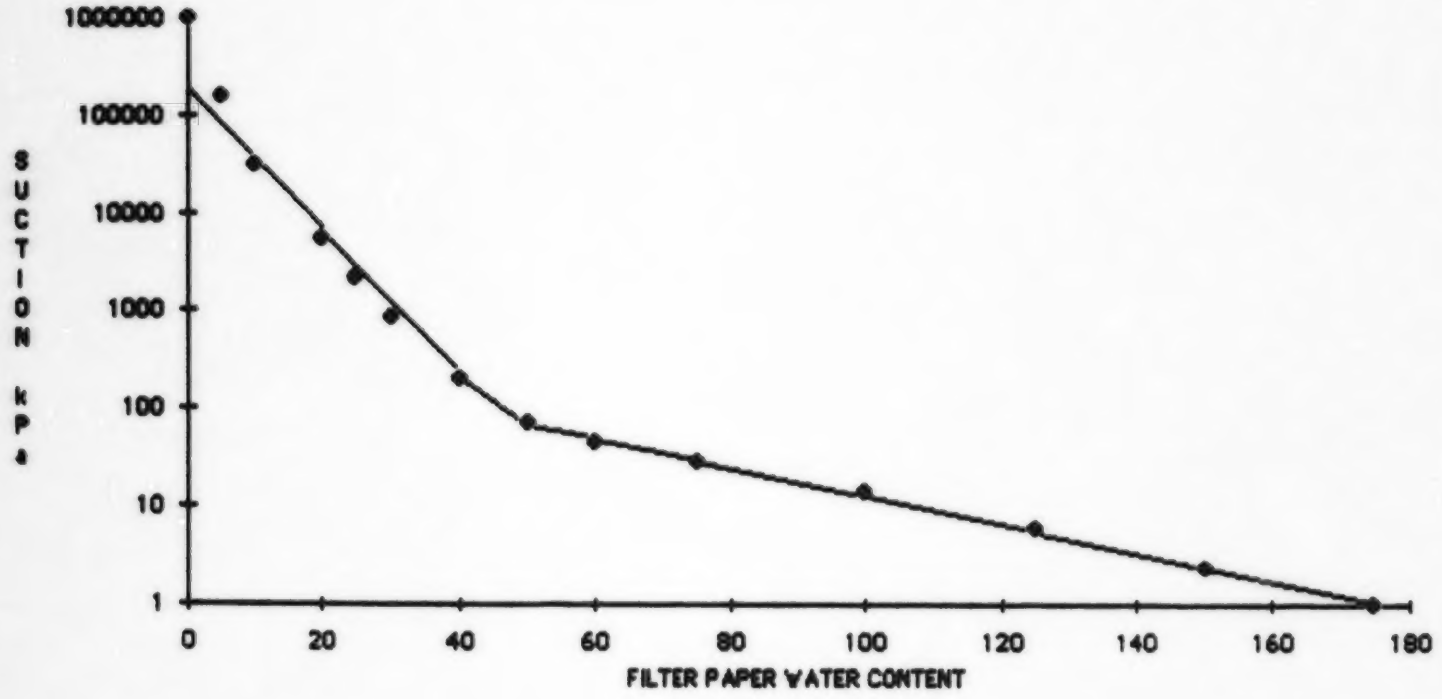

FIGURE 61 : CALIBRATION CURVE FOR WHATMAN No. 42 FILTER PAPERS
(AFTER FAWCETT AND COLLIS-GEORGE 1967)

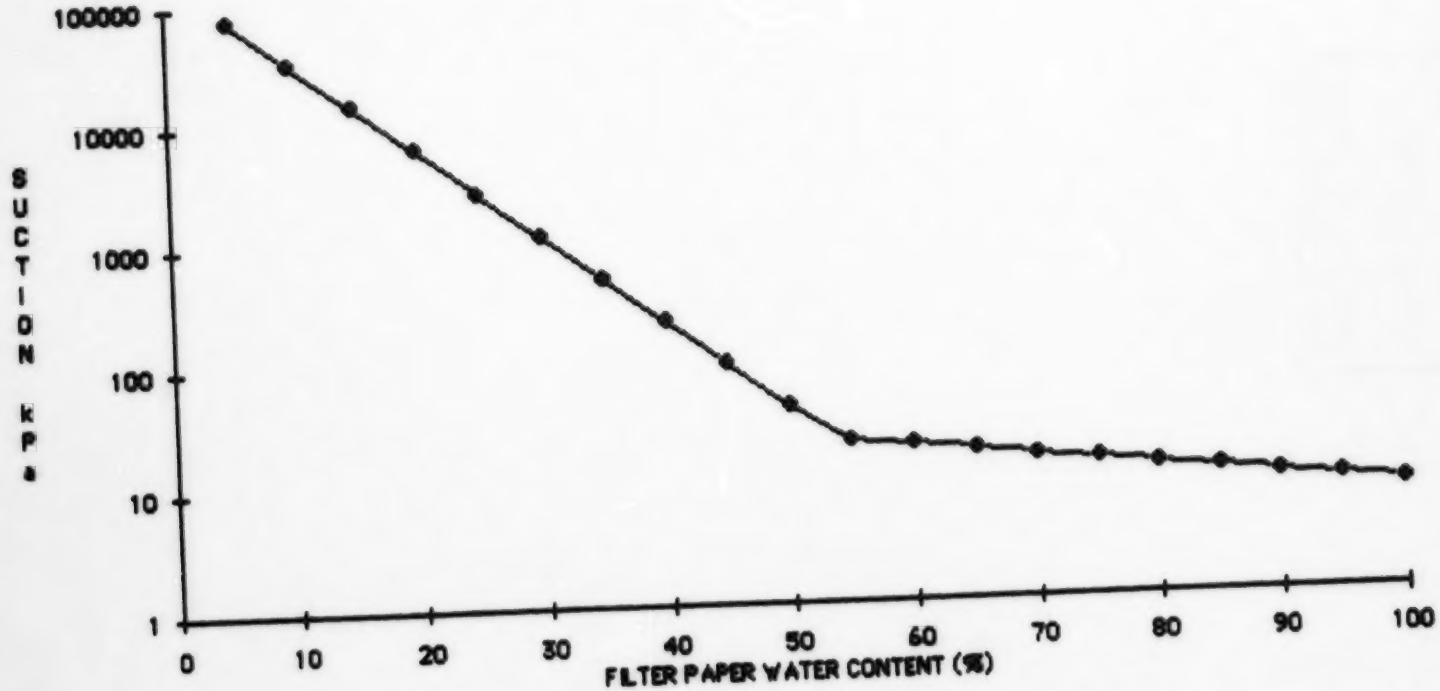

FIGURE 62 : WATER CONTENT OF FILTER PAPER VERSUS SUCTION
AFTER McQUEEN AND MILLER (1968)